State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2015

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by

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ABSTRACT

Fisheries and Oceans Canada is responsible for the management and protection of marine resources on the Pacific coast of Canada. An annual State of the Pacific Ocean meeting is held to review the physical, biological and selected fishery resources and present the results of the most recent year's monitoring in the context of previous observations and expected future conditions. The workshop to review conditions in 2015 was held March 1 and 2, 2016 at the Vancouver Island Conference Centre in Nanaimo, B.C. The waters off Canada's west coast experience strong seasonality and considerable freshwater influence and include relatively protected regions such as the Strait of Georgia as well as areas fully exposed to the open ocean conditions of the Pacific. The region supports ecologically and economically important resident and migratory populations of invertebrates, groundfish, pelagic fishes, marine mammals and seabirds.

Observations of the marine environment in 2015 identified the continued presence of a large pool of very warm water in the Northeast Pacific Ocean (colloquially known as the "Blob") with surface waters over 3 °C above normal at its peak in July. The equatorial water of the eastern Pacific also began to warm and by the fall of 2015 a strong El Niño was building. By the end of 2015 the warm surface water anomaly in the Northeast Pacific Ocean had decreased to about 1 °C above normal, while the subsurface waters to a depth of 100 m still remained significantly warmer than normal. These ocean conditions influenced the weather experienced during 2015, and impacted the biological ecosystems on regional and local scales, including changes at the base of the food web such as exceptional blooms of phytoplankton, unusually high abundances of gelatinous zooplankton, and range extension northwards of plankton and fish species more commonly found further south.

A special session at the meeting was convened to focus on the monitoring and research being undertaken on the freshwater conditions relevant to the health of anadromous fish populations.

RÉSUMÉ

Pêches et Océans Canada est responsable de la gestion et de la protection des ressources marines de la côte ouest du Canada. Une rencontre annuelle sur l'état de l'océan Pacifique a lieu pour réviser les conditions physiques, biologiques, ainsi que certaines ressources halieutiques et pour présenter les résultats des derniers recensements et les mettre en contexte avec les observations précédentes et les conditions futures basées sur les prédictions. Un atelier pour réviser les conditions de 2015 a eu lieu à Vancouver Island Conférence Centre, Nanaimo, C.B., les 1-12 mars 2016. En général, les eaux canadiennes du pacifique ont démontré une forte saisonnalité sous l'influence considérable d'apport en eaux douces, incluant des régions relativement protégés comme le détroit de Géorgie ainsi que des régions complètement exposés aux conditions en vigueur au large des côtes du pacifique. La région supporte des populations résidentes et migratoires d'invertébrés, de poissons, de mammifères marins et d'oiseaux de mer qui sont importantes d'un point de vue écologique et économique.

Les observations des conditions marines au début de 2015 ont indiqué la présence continue d'une large masse d'eau chaude dans le nord-est de l'océan Pacifique, (familièrement connu sous le nom "The Blob") avec les eaux de surface de plus de 3 °C supérieures à la normale, à son apogée en Juillet. L'eau équatorial du Pacifique a commencé à se réchauffer et à l'automne de 2015 un fort El Nino était présent. À la fin de 2015, l'anomalie chaude de l'eau de surface dans l'océan Pacifique Nord a diminué à environ 1 °C au-dessus de la normale, mais les eaux sous-jacentes, à une profondeur de 100 m, sont demeurées beaucoup plus chaudes que la normale. Ces conditions océaniques ont influencé le climat en 2015, et les écosystèmes biologiques à l'échelle régionale et locale.

Une session spéciale a été convoquée pour mettre l'accent sur le suivi et les recherches sur les conditions d'eau douce pertinentes pour la santé des populations de poissons anadromes.

1. HIGHLIGHTS

- The annual DFO State of the Pacific Ocean meeting was held March 1 and 2, 2016 at the Vancouver Island Conference Centre in Nanaimo, B.C.
- Two significant ocean events were observed in the Northeast Pacific in 2015: the continued warming of the upper 100 m of the central Gulf of Alaska (colloquially referred to as the "Blob") during the first half of 2015, and a strong El Niño during late 2015 and early 2016.
- Phytoplankton blooms off the west coast of Vancouver Island were observed earlier (May) and remained longer (August) than normal. This bloom included species which produce domoic acid, a human neurotoxin, but, in contrast to widespread shellfishery closures along the US coast, only three areas along the west coast of Vancouver Island were closed to shellfish harvesting as a consequence of this bloom.
- The very warm water anomaly did not induce widespread Sockeye Salmon recruitment failures in 2015, but did influence the return timing and size-at-age traits of many populations. The warm ocean conditions in 2015 and El Niño in 2016 are likely to have produced unfavourable survival conditions for Central-to-South Coast salmon that went to sea in 2015, and therefore reduced returns in 2016-2018 of these stocks are expected.
- A special session on freshwater conditions and anadromous species in 2015 identified the low snowpack and early spring river runoff in southwestern B.C., and the warm water temperatures in late summer, as factors contributing to widespread losses of return migrating adult Sockeye Salmon.

1.1. Northeast Pacific and outer BC coast

- Land and ocean temperatures made 2015 the warmest year on record both globally and in the Northeast Pacific; 2014 is the second warmest year on record.
- Land surface temperatures in B.C. in 2015 were the warmest in the past 116 years, and new seasonal records during the first half of the year were established for many regions. Snowmelt was early and rapid in 2015, leading to above normal streamflow in the spring and below normal in late summer.
- Indicators of the spring transition to upwelling conditions, including wind, currents and waves off the west coast of Vancouver Island, showed a near average timing of mid-April.
- The pool of warm water, known colloquially as the Blob, that had dominated the upper 100 m of the Gulf of Alaska in 2014 remained a coherent feature until August 2015. After August the sea surface temperatures (SST) of Northeast Pacific decreased to levels more consistent with typical conditions, although sub-surface temperatures to a depth of 100 m remained much warmer than normal.
- During the latter half of 2015 the equatorial waters of the eastern Pacific warmed significantly, consistent with the development of strong El Niño conditions.
- Offshore SST data collected at west coast ODAS meteorological NOMAD buoys showed increased temperatures at times exceeding 3 °C above normal, with record high SSTs observed in the summer of 2015.

- Coastal SST observed at lighthouses showed warmer temperatures in 2015 than 2014. The average annual increase in SST for all stations was 1.98 °C (standard deviation of 1.02 °C).
- Increased stratification of the upper ocean associated with the Blob restricted the renewal of nutrients by vertical transport in the winter of 2014/15. As a result, nitrate depletion in the surface coastal waters extended farther westward in June and August 2015.
- Phytoplankton blooms off the west coast of Vancouver Island were observed earlier (May) and remained longer (August) than normal.
- The warmer ocean temperatures brought warm water species of zooplankton and fish to the west coast of Canada. Southern species of copepods (poor food for fish) were caught in increasing numbers in the survey areas west of Vancouver Island while there were fewer sub-Arctic and boreal copepods. Monitoring revealed a considerable increase in the presence of gelatinous animals off the west coast of Vancouver Island (such as doliolids).
- Off the west coast of Vancouver Island the biomass of Smooth Pink Shrimp declined from the peak in 2014, but remained among the highest observed (since surveys began in 1973). Walleye Pollock and Pacific Halibut also had record high biomass in 2014, and their biomass also declined in 2015 to near-normal amounts.
- The triennial Canada-U.S. survey for Pacific hake conducted in summer 2015 identified the largest biomass of hake in the history of the survey. However, the fish were not aggregated as usual resulting in many Canadian hake fishers switching to the shrimp fishery. Significant aggregations of age-1 hake were observed at the southern end of Vancouver Island.
- During the La Perouse acoustic trawl survey, there were more Pacific Herring observed along the southwest coast of Vancouver Island than in previous years (2013-2014), and
- In 2015, there was an increase in Pacific Herring biomass in three areas (Prince Rupert, Strait of Georgia, Central Coast). The biomass of Pacific Herring in three major stock areas (Haida Gwaii, Central Coast, and west coast of Vancouver Island) have experienced prolonged periods of low biomass in the absence of fishing. The two areas that are open to fishing maintain stable or high biomass estimates (PRD and SOG).
- In all five major stocks of Pacific Herring, there was a declining trend in weight-at-age beginning in the 1980s through 2010, with an increase or leveling off in recent years.
- Eulachon catch per unit effort observations from an annual spring multispecies trawl survey were relatively high in 2013 to 2015 compared to previous years. In 2015, there was only one mode of Eulachon lengths where normally a bi-modal distribution has been observed.
- The growth of juvenile Coho Salmon off the west coast of Vancouver Island in 2015 was above average; a positive indicator for high survival. However, physical indicators associated with smolt survival are less positive.
- Anomalously warm ocean conditions in 2014-15 did not induce widespread salmon recruitment failures in 2015 but did influence the return timing, straying rates and size-at-age traits of many salmon populations.
- The 2015 returns of Okanagan Sockeye were far above average and Barkley Sound Sockeye achieved a new record return of 2.1 million fish; returns of Fraser Sockeye and Pink were half of that expected in 2015.

- The association of Albacore Tuna with particular ocean temperatures (14-19 °C) coincides with an unusually high abundance northwest of Haida Gwaii in 2014, and off the west coast of Vancouver Island in 2015.
- The diets of nestling Rhinoceros Auklets on Pine Island in 2015 included considerably less juvenile salmon than observed in the preceding three years, but the amount fed to nestlings at Lucy Island, in Chatham Sound in northern B.C., was normal.
- Observations from ships and recordings of vocal activity from autonomous acoustic recorders deployed data in along B.C.'s north coast show the re-occupation of historically occupied habitat in Hecate Strait, Queen Charlotte Sound and Caamaño Sound by Fin Whales. Fin Whales are present year round. The region appears to be important for foraging and possibly breeding and calving.

1.2. Strait of Georgia

- A rapid and early snowmelt introduced large volumes of fresh water resulting in negative salinity anomalies in the first part of the year, and positive anomalies after the summer.
- Water temperatures in the Strait of Georgia and Juan de Fuca Strait during 2015 were up to 2 °C warmer than normal.
- The UBC model of the physics and lower trophic levels in the Strait of Georgia predicted the 2015 spring bloom would occur in mid-March. The maximum phytoplankton biomass was registered by ferry instruments on March 11, 2015. Interpretation of (MODIS) satellite imagery, and fluorometer data from the central Strait of Georgia, showed the start date of the bloom as March 7 in the southern Strait and February 21 in the northern Strait. This is the earliest spring bloom in this region since 2005.
- Monitoring of carbonate parameters (ocean acidification) by the Hakai Institute in the northern Strait of Georgia showed winter pH_T and Ω_{arag} levels near 7.8 and 0.9, respectively. Ω_{arag} levels less than 1 indicate the tendency for aragonite dissolution. The spring phytoplankton bloom drove a large increase in both pH_T and Ω_{arag} to 8.4 and 2.8, respectively, and these levels persisted until autumn except during periodic wind mixing events.
- Three natural drivers (SST at Entrance Island, wind speed at Vancouver airport, and the North Pacific Gyre Oscillation Index) with the explanatory power to identify shifts in ecosystem state in the Strait of Georgia showed that 2015 clustered with 2013 and 2014, but it was the weakest grouping of any year in the 1970-2015 time series.
- Fraser River Eulachon spawning biomass (as estimated with an egg and larval survey) increased to 317 tonnes in 2015; the spawning biomass was well below 120 t during 2004 to 2014.
- The relative biomass of age-0 herring (as sampled by the SOG juvenile herring survey) was lower and stable during 2013-2015, compared to peaks within the time series (1992-2015). Also in 2015, age-0 herring were heavier for a given length.
- Tracking of out-migrating juvenile Steelhead with internally-implanted acoustic tags show marine survival was higher in the central Strait of Georgia than in the northern Strait of Georgia to Queen Charlotte Sound, and that Burrard Inlet is associated with higher mortality.
- In recent years (2010-2014 return years) productivity, and consequently returns have increased across 19 Fraser Sockeye stocks (those with stock-recruitment data). In 2015 although productivity and returns for the total aggregate of these stocks has been poor there was considerable variability among these stocks.

1.3. Freshwater conditions and anadromous species

- In 2015, the high water temperatures off the coast of B.C. and a strong El Niño weather pattern affected Fraser River freshwater discharge and temperature conditions. Salmon in water temperatures above 18 °C show signs of decreased swimming performance, and above 20 °C can suffer increased mortality, disease, and legacy effects on egg quality. Warmer water and lower discharge were associated with widespread *en route* loss estimates for most Fraser Sockeye stocks, but water conditions improved for spawning periods.
- A chlorophyll time series (2002-2012) has been validated for Chilko Lake based on the European MERIS sensor aboard the ENVISAT satellite.
- Empirical evidence suggest a correlation between early phytoplankton blooms and larger smolts, and that strong summer primary production is associated with better growth, freshwater survival, and smolt survival.
- Annual estimates of Chinook abundance by the Pacific Salmon Commission show that relative abundance has been consistently higher in northern fisheries and that there have been three peaks in abundance (1988, 2003, and 2014).
- In 2015 Barkley Sound Sockeye returning to the Somass River, and Columbia River Sockeye returning to the Okanagan River were influenced more by the anomalous warm temperature regime than the discharge conditions in their rivers of origin.
- The declining returns of Coho Salmon in the Salish Sea are attributed to neither open ocean conditions nor fresh water conditions but rather conditions within the Salish Sea itself.

2. INTRODUCTION

Fisheries and Oceans Canada, Pacific Region, conducts annual reviews of physical, chemical and biological conditions in the ocean, to develop a picture of how the ocean is changing and to help provide advance identification of important changes which may potentially impact human uses, activities, and benefits from the ocean. These reviews take the form of one to two day meetings, usually held in February or March of the year following the year under review. The first meeting was held in 2000 to assess conditions in 1999; reports from these reviews are available at

http://www.dfo-mpo.gc.ca/oceans/publications/index-eng.html

or by conducting a web search using the search terms: "DFO, Pacific, Ocean Status Reports" and scrolling to "Oceans-reports and publications", then scrolling down to "State of the Pacific Ocean".

Reviews and reports from 2007 to 2013 were conducted under the direction of the Fisheries & Oceans Canadian Science Advice Secretariat (CSAS). In 2014, these State of the Pacific Ocean reviews were moved to a separate process and are now presented as Fisheries & Oceans Canada Technical Reports. The report from 2015 (of conditions in 2014) is available at

http://www.dfo-mpo.gc.ca/Library/358018.pdf

In 2016, the meeting on conditions in 2015 took place on March 1 and 2 at the Vancouver Island Conference Centre in Nanaimo, B.C. The agenda for the meeting is presented in Appendix 1, and the participants are listed in Appendix 2.

This technical report presents the highlights and summaries of the presentations and discussions at the workshop. These summary reports are not peer reviewed, and present the status of data, interpretation, and knowledge as of the date of this meeting. For use of, or reference to, these individual presentations, please contact the individual authors.

3. OVERVIEW AND SUMMARY

The unusually warm ocean water observed in the central Northeast Pacific (Figure 3-1) in 2014 continued in 2015 with surface temperatures in July peaking at more than 3 °C above normal. While the sea surface temperatures in this area (Figure 3-2) cooled to normal temperatures in the second half of the year, above normal temperatures persisted in the subsurface waters. Changes to the stratification of the surface waters to more normal conditions suggest that the nutrient supply will also return to normal.

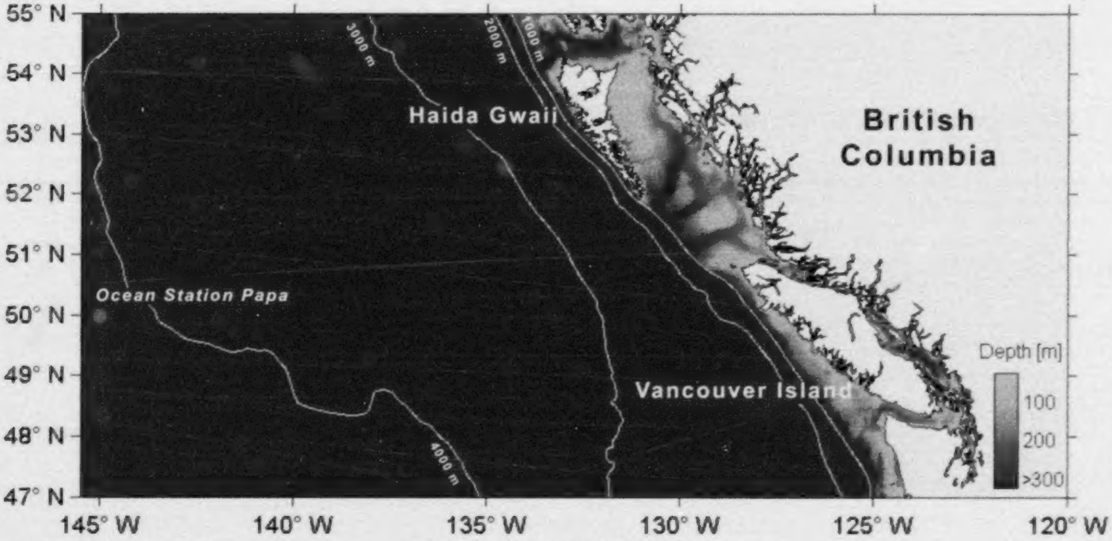

Figure 3-1. Map of the Canadian waters discussed in this report.

In the autumn of 2015 increased sea surface temperatures in the eastern Pacific equatorial waters were associated with the development of a strong El Niño, which was expected to reach Canadian Pacific waters by the end of 2015. Identification of this El Niño signal in coastal temperature data, however, was complicated by the already warm conditions caused by the NE Pacific warm anomaly. Stronger than average surface winds appeared to have mixed the warm temperature surface waters downward in late 2015 and early 2016, which initially intensified the pycnocline around 100 m and re-oxygenated these upper layers. By the first half of 2016, however, this strong pycnocline appeared to have weakened, with the warmer waters spread more broadly over the NE Pacific.

The warm ocean conditions created unusual plankton blooms in 2015 (Figure 3-3). In the early July survey at the shelf break off Vancouver Island, *Pseudo-nitzschia fraudulenta* (a potential domoic acid producer) comprised 32% of all diatoms, and 19% of all microplankton sampled. Domoic acid concentrations were considerably higher along the US west coast, causing marine mammal deaths and closing fisheries. Only three areas along Vancouver Island had domoic acid concentrations above the human heath cut-off level, which were therefore closed to harvest of shellfish during July 2015.

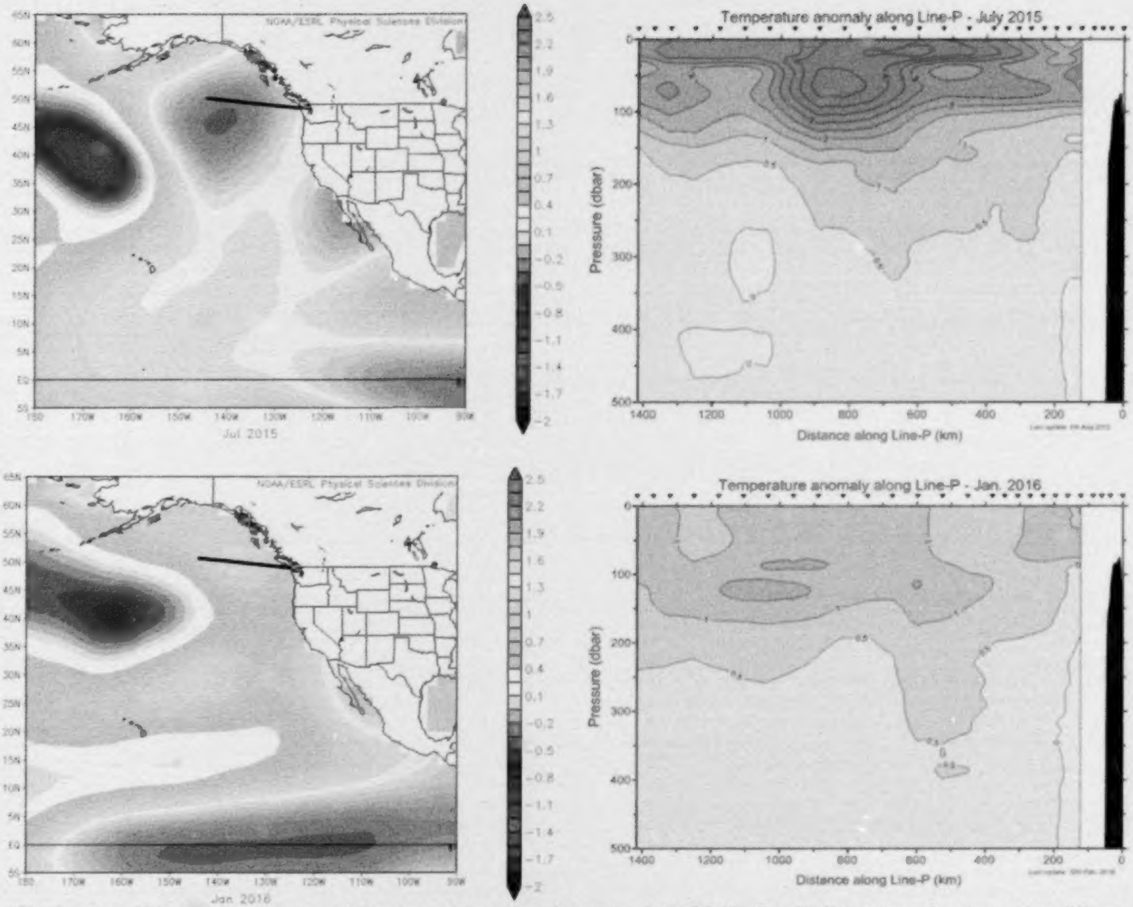
NOAA/ESRL Physical Sciences Division
Jul 2015
Jan 2016
2.5
2.2
1.9
1.6
1.3
1
0.7
0.4
0.1
-0.2
-0.5
-0.8
-1.1
-1.4
-1.7
-2
Temperature anomaly along Line-P - July 2015
Temperature anomaly along Line-P - Jan. 2016
Pressure (dbar)
Distance along Line-P (km)

Figure 3-2. The upper panels show ocean temperatures in July 2015, the bottom panels show conditions in January 2016. The panels on the left show contours of sea surface temperature anomaly data from the National Oceanic and Atmospheric Administration Extended Reconstructed Sea Surface Temperature (NOAA_ERSST_V3) data which includes information from satellites, ships, moored and drifting buoys. The Line P monitoring transect is shown extending from the coast to Station Papa (145° W, 50° N). The panels on the right are derived by interpolating observations from Argo floats along Line P (courtesy Howard Freeland).

The warmer ocean temperatures brought warm water species of zooplankton and fish to the west coast of Canada from both the Gulf of Alaska and the coast of California. Southern species of copepods were caught in increasing numbers in the survey areas west of Vancouver Island. Monitoring revealed a considerable increase in the presence of gelatinous animals off the west coast of Vancouver Island, especially of doliolids. Neither of these types of plankton (southern copepod species or gelatinous plankton) are particularly good food for fish such as Pacific Salmon.

These warm water temperatures also enabled northward rage extensions of fish which are normally found further south such as Albacore Tuna (including unusually high abundances in summer northwest of Haida Gwaii) and ocean sunfish (*Mola mola*). Pacific Hake, a warm water species, was more abundance off the west coast of Vancouver Island than in previous years, and included age-1 hake which have not been observed in this region in recent years. Also off the west coast of Vancouver Island, surveyed biomasses of Smooth Pink Shrimp, Walleye Pollock, and Pacific Halibut declined towards more normal values from their record highs in 2014. In summer, Pacific Herring were distributed more broadly than previous years in this same region, and further offshore.

The growth of juvenile Coho Salmon off the west coast of Vancouver Island was above average, although physical and biological indicators of smolt survival indicated opposite trends. The 2014-2015 anomalously warm water conditions in the North Pacific Ocean did not induce widespread salmon recruitment failures in 2015 due to common ocean effects as some feared but, did influence return timing, straying rates and size-at-age traits of many salmon populations originating from eastern Pacific waters from south-central Alaska, through B.C., Washington and Oregon. The impacts of a warmer than average ocean in 2014-2015 followed by the El Niño in spring 2016 suggest survival unfavourable conditions for juvenile salmon making sea entry from the B.C. central to south coast in those years so significant reductions in returns to many populations (Okanagan-Columbia River salmon; Barkley and west coast Vancouver Island salmon) may be expected in 2016-2018.

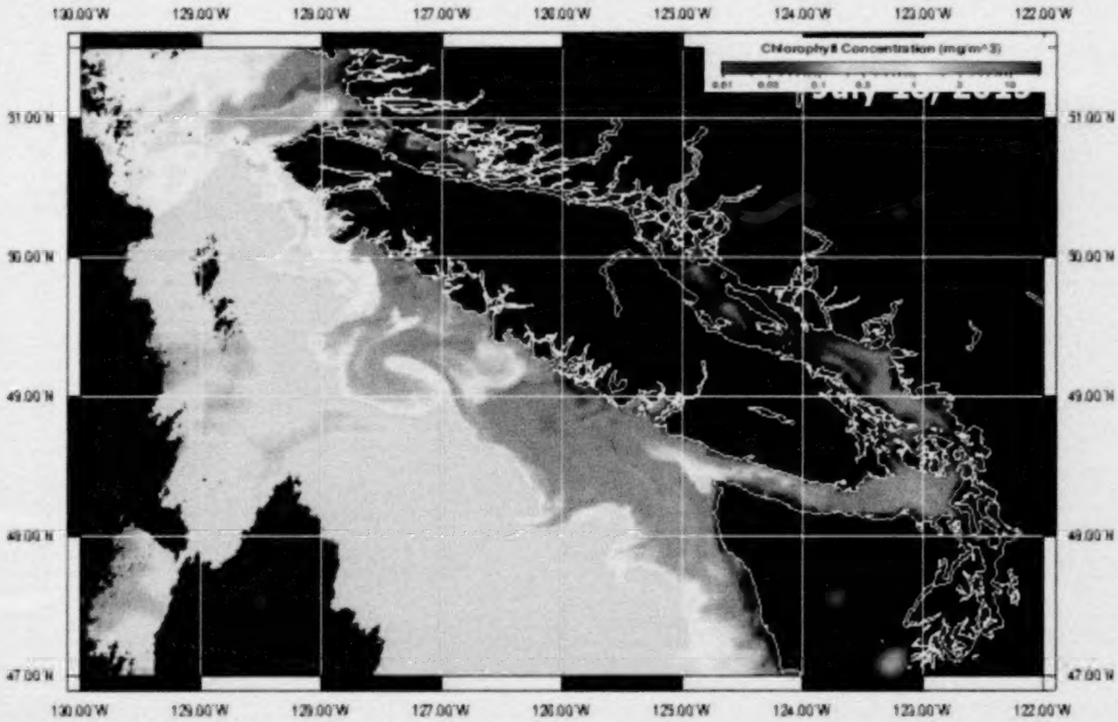

Figure 3-3. NASA MODIS Aqua standard processing chlorophyll image showing high chlorophyll concentrations off the west coast of Vancouver Island in the summer of 2015.

The fresh water input to the Strait of Georgia was above normal in early 2015 due to above average precipitation and air temperatures contributing to an early and rapid snowmelt. Fraser

River discharge rates at Hope were five times higher than normal in April (Figure 3-4). The lack of snowmelt later in the summer, and lower than average rainfall, resulted in above average river temperatures and low flow conditions until autumn. In 2015 an additional 40 days of water temperatures above 18 °C, associated with stress in salmon, were observed in southwestern B.C. and Vancouver Island rivers.

The spring bloom in the northern Strait of Georgia occurred about one month earlier (15 February) than in the southern Strait of Georgia. The occurrence of the spring phytoplankton bloom in mid-March in 2015 was the earliest spring bloom since 2005. The biomass of juvenile Pacific Herring in the Strait of Georgia in 2015 was similar to the previous two years, and the fish were heavier for a given length. Catches of juvenile Coho Salmon in the Strait were above average, and also with larger sizes. In recent years (2010-2015 return years), productivity has varied across the 19 Fraser Sockeye stocks with stock-recruitment data. Marine and freshwater factors contribute to these differences. Chilko Lake is the only stock where total survival can be partitioned into freshwater and marine over a long time series. In the past decade, this stock has generally exhibited above average freshwater survival and below average marine survival. Fraser Sockeye returns in 2016 (2.3 million at the 50% probability level) are expected to be below the cycle average (3.9 million), due to the very low brood year escapements for many stocks in 2012. Considering the inconsistent productivity responses across Fraser Sockeye stocks in 2015, it is unclear how productivity for the 2016 returns will be affected by the unusually warm conditions in the NE Pacific (i.e. whether returns will fall above or below the 50% probability level forecasts).

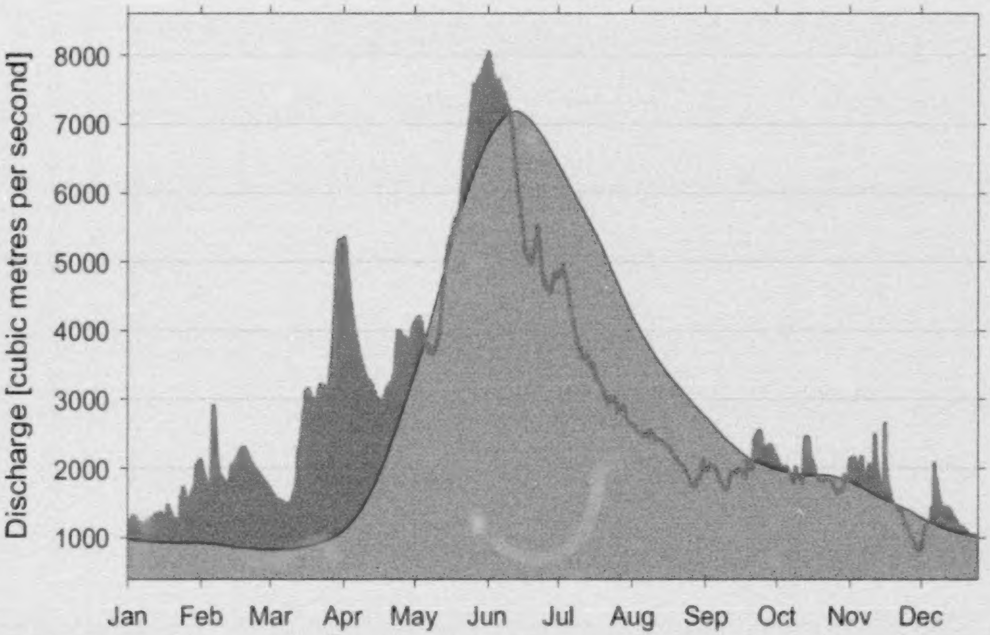

Figure 3-4. Fraser River flow at Hope in 2015 (blue) and the average flow based over the past 103 years (data source: Water Survey of Canada).

4. ACKNOWLEDGEMENTS

The authors and contributors to this Technical Report wish to thank all the officers and crew of the many vessels that have been involved in collecting data and maintaining monitoring stations for these studies. Without their assistance many of the reports in this document would not be possible.

Individual reports on conditions in the Northeast Pacific and British Columbia's outer coast

5. BRITISH COLUMBIA HYDROCLIMATOLOGICAL CONDITIONS, 2015

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5.1. Highlights

- Air temperature observations set a record high for the B.C.-wide average. Regionally, annual records were set in the southwestern two thirds of the province.
- Seasonally, spring was the most anomalously warm while winter and summer contained at least one region with record breaking warmth and were much above elsewhere.
- Precipitation was near normal or above normal in seasonal averages, but included very dry months.
- Snow accumulation was near or above normal in central B.C., below normal in the northwest and southeast and extremely low in southwest B.C.
- Snow melted rapidly in spring leading to very low snowpacks at the end of the season.
- Hydrologically, streamflows were much above normal in the spring province-wide leading to much below normal to record low province-wide by summer.

5.2. Introduction

In early 2016, three of the major centres for global climate monitoring determined with high confidence that 2015 was the warmest year on record by a substantial margin (Hansen 2010, Osborn and Jones 2014, Gleason et al. 2015, Huang et al. 2015, GISTEMP 2016). All centres point toward ongoing greenhouse warming coupled with the development of a very strong El Niño as causes of the record warmth. The cyclical La Niña/El Niño may influence global climate by storing and then releasing energy in the deep Pacific ocean (down to 700 m; Meehl et al. 2011). More locally, the seasonal weather of British Columbia is directly influenced by El Niño via atmospheric teleconnections spanning the North Pacific Ocean and North America. Furthermore, during the winters of 2013, 2014 and 2015 anomalously high atmospheric pressure and the attendant dearth of storms over the Northeast Pacific (Bond et al. 2015; Hartmann 2015) resulted in a very large region of record warm ocean surface temperatures to the west of British Columbia – a pattern inadvertently coined the "Blob" by climatologists in Washington State. These combined events likely had a strong warming effect on the weather that British Columbia experienced throughout 2015. In this article we discuss conditions in the province in terms of seasonal averages of daily minimum and maximum temperature and precipitation, the evolution of the winter and spring snowpack, and the effects of these on spring and late summer streamflow throughout B.C.

5.3. Data

Seasonal temperature and precipitation anomalies were calculated from data gathered through a data sharing agreement among the B.C. Ministries, B.C. Hydro and Environment Canada. These data are assembled into a centralized database housed at the Pacific Climate Impacts

Consortium (PCIC) at the University of Victoria and made available via the web. Data are gathered from both hourly and daily sources. The database is updated with near real-time data feeds from the Ministry of Transportation and Infrastructure, the Ministry of Forests Lands and Natural Resource Operations Wildfire Management Branch and Environment Canada. Basic quality control is done by the network operators before the data is made available to PCIC and no further quality control was done for this analysis.

Anomalies are computed on a seasonal basis using monthly climatologies calculated using the 1971 – 2000 climate normal period. For temperature, the anomalies are computed as a simple difference between the climate normal and the observed three-month average. For precipitation, anomalies are computed on a relative basis as *(P-Pnorm)/Pnorm * 100*. *P* is the observed total precipitation for the season and *Pnorm* is the long-term average amount. Thus a season in which no precipitation was recorded will receive an anomaly of -100%. A normal precipitation season will have an anomaly of 0% etc.

To compute regional anomalies from station data we use the so-called eco-provinces which define regions of ecological and climatological coherence within B.C. First anomalies at individual stations are interpolated to a regular 0.5 degree grid using thin-plate splines. Next, the gridded anomalies are sampled within a given region and an average of those anomalies is taken. This yields an area weighting of the stations within a region and also provides support for regions that contain few observational stations. The regions are then ranked among the averages from the period of record spanning from 1900 through 2015. These percentile ranking are displayed in this analysis.

For seasons, we combine three complete months such as December, January and February for winter and March, April and May for spring etc. Because of this, the annual anomalies computed over the months of 2015 are slightly different than what would be computed combining the individual seasons because, seasonally, December 2014 is included in the analysis of 2015.

Streamflow data were gathered from the national hydrometric network and anomalies were computed similarly to those for precipitation in the above analysis. Streamflow was averaged through the seasons and compared with averages from data available since 1970. Because numerous observational periods of record go earlier than 1970, the record extremes in this analysis are only relative to the 46-year timeframe and in some cases may not be true records in the full length of the data. The purpose of this analysis is to show that 2015 was extreme and that extreme values existed province-wide. Hydrometric data are quality controlled through roughly 2012 at present, so data in this analysis may contain errors and may be subject to revision in the future.

Snow survey and automated snow pillow data are gathered by the Ministry of Environment and cooperatively through partner agencies. The data are analyzed by the Ministry of Forest Lands and Natural Resource Operations' River Forecast Centre as part of its tracking of potential flood risks due to spring snowmelt. Anomalies are calculated in a similar manner as those for precipitation except the anomaly is expressed as a ratio relative to the long-term average snow water equivalent. Station anomalies are averaged within regions to arrive at regional values.

5.4. Winter

Starting with the winter (spanning December 2014 through February 2015) the conditions that lead to the maintenance of the Blob at this time were also associated with higher than normal pressure over British Columbia which, in turn, led to warmer than normal temperatures across the entire province for the season. The storms that did come through produced sufficient precipitation to keep the province at or above normal for rain and snowfall, with the central part of the province receiving larger than normal precipitation amounts leading to above normal snowpacks (Figure 5-1 c and d). For both daily maximum and minimum temperature (Figure 5-1 a and b), the far southwestern corner of the province experienced record-breaking warmth and all but the northeast corner of the province experienced much warmer than normal temperatures with values that rank in the top 10 for the past 116 years.

5.5. Spring

The warmth and relative wetness of winter set the stage for spring. Over the period from March through May, precipitation patterns remained similar to those of winter, with much above normal precipitation amounts in the central parts of the province and above normal precipitation everywhere except the far northeast corner, where precipitation was below normal (Figure 5-2c). Temperatures, however, continued to be very warm. The behaviour of minimum and maximum temperatures also began to differ from each other in terms of how extreme the anomalies were. Minimum daily temperatures in spring were of record-breaking warmth for much of the western and central regions of the province (Figure 5-2b). Elsewhere, in the north and eastern parts of the province, minimum temperature was in the top 7 years of the long-term period of record. Maximum temperatures set a record for warmth in the north and were in the top 4 warmest years everywhere else except in the region around southern Vancouver Island and the city of Vancouver which ranked 11th warmest. The warm spring conditions likely contributed to an early start to the fire season in the province and what would lead to a more active than normal fire season in B.C. These warm spring conditions also led to much lower than normal late spring snowpacks in much of the province and, eventually, the earlier than normal loss of the winter's snow despite relatively wet conditions (Figure 5-2d).

5.6. Summer

Although summer started very warm, conditions began to moderate as the season progressed, eventually leading to a relatively cool and wet August. Overall, minimum temperatures were still very warm (Figure 5-3b). Records were still broken in the southwest part of the province and were in the top 8 warmest years for all regions but the far northeast. The behaviour of maximum and minimum temperatures continued to diverge with maximum temperatures attaining less extreme values than minimum temperatures. Average maximum temperatures reached much above normal values in the southeast with near or above normal conditions for the remainder of the province. Precipitation was near normal for the southern half of the province and ranged from above normal to much above normal in the north (Figure 5-3c). The simultaneous much above normal precipitation, warm daily minimum temperatures and near normal maximum temperatures suggests that unusually warm, cloudy conditions prevailed in the north. We speculate that the warm ocean temperature associated with the Blob helped to provide warm, moist conditions leading to this combination of seasonal anomalies. The summer season was punctuated by a very strong cyclonic storm that impacted southwest British Columbia in the last few days of August. This storm broke records for how low the air pressure was at its centre and drove strong winds which caused numerous impacts across SW British Columbia.

5.7. Fall

The trend toward more normal conditions that began in late-summer continued into the fall. During this period temperature returned to near normal or above normal (as defined earlier) for both daily maximums (Figure 5-4a) and minimums (Figure 5-4b). For precipitation, conditions were similarly near normal with only the southeast corner of the province above or much above normal (Figure 5-4c).

5.8. The Streamflow Response

The evolution of seasonal temperature, precipitation and concurrent snow accumulation and melt had major impacts on the streamflows observed in B.C. in 2015 (Figure 5-5). As described above, very warm temperatures in spring led to rapid declines in snowpack, in some cases from much above normal snowpack to much below normal in the span of three months. This rapid decline in snow along with ongoing normal or above normal precipitation led to much above normal streamflow almost uniformly across the province. Almost everywhere March, April, May streamflows were in the top 10 % of the 46-year record from 1970 through 2015 for the season. The consequence of the rapid, early loss of snow cover across the province was much reduced water supplies for the remainder of the year. Combined with much above normal to record breaking temperatures and periods with little precipitation, these conditions led to much below normal streamflows by the July, August, September period. During this time, the majority of stations recorded streamflows in the lowest 25th percentile with many below the 10th percentile to record lows within the 46-year context of this analysis. The exception to this is central B.C. where some stations reported streamflows that remained near- to slightly above-normal. This region sustained above-normal to normal snowpacks into late spring and this water source likely helped maintain normal streamflows. Furthermore, several of these watersheds have glacier cover whose melting ice may have contributed, but this is speculation because there are no observational data for glaciers in these watersheds.

The observed transition from high springtime streamflows to low summertime flows bears a strong resemblance to projections of streamflow change under numerous climate projections. For watersheds driven by snowmelt, those projections show a triad of effects: higher flows in the early spring along with earlier onset of melting, an earlier and lower peak flow, and reduced late summer flows owing to lower snowpack and increased evapotranspiration (Schnorbus and Cannon 2014). More detailed analysis of the 2015 hydrograph for several watersheds exhibits all of these behaviours suggesting that 2015 may be a useful analogue for future streamflow behaviour in British Columbia.

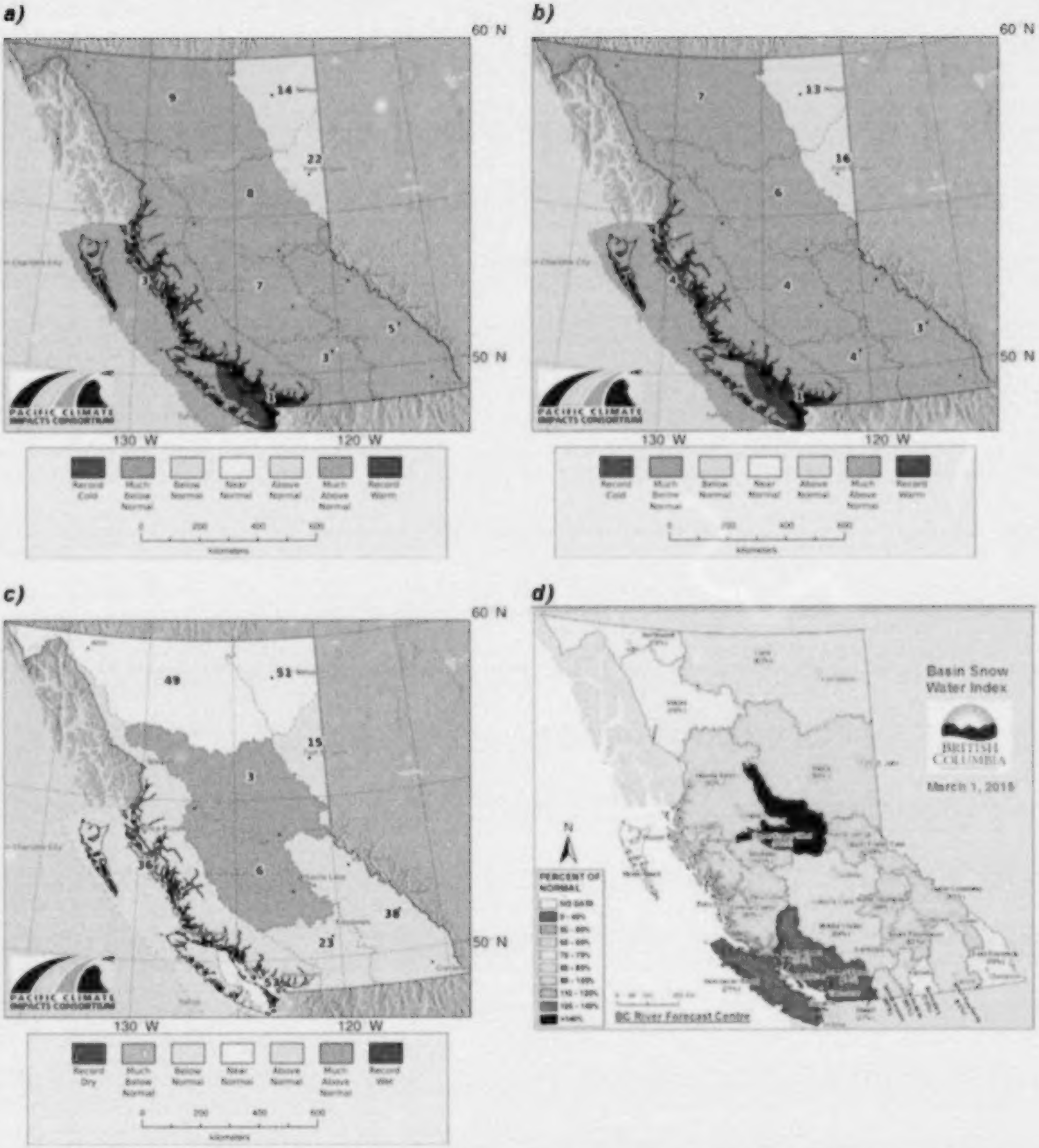

a)
b)
c)
d)
60 N
50 N
130 W
120 W
9
14
22
8
7
3
5
3
7
13
16
6
4
4
3
4
49
51
15
3
6
36
38
23
53
Record Cold
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warm
Record Dry
Record Wet
0
200
400
600
Kilometers
PACIFIC CLIMATE IMPACTS CONSORTIUM
Basin Snow Water Index
BRITISH COLUMBIA
March 1, 2015
N
PERCENT OF NORMAL
NO DATA
BC River Forecast Centre

*Figure 5-1. Panels **(a), (b), and (c)** depict winter (December 2014, January 2015 and February 2015) temperature and precipitation anomalies colorized by ranking among the 116 years of data from 1900 through 2015. Minimum temperature is shown in panel **(a)**, maximum temperature in panel **(b)**, and precipitation in panel **(c)**. Colour classification is such that Near Normal corresponds to the 33rd to 66th percentiles, Above Normal to the 66th through 90th percentiles, Much Above Normal to 90th to all but the record year. The final category is for record which is the 99.2 percentile. Analogous categories for the below normal values are 33rd to 10th, 10th to 0.8 and record for Below Normal, Much Below Normal and Record respectively. Numbers indicate ranking relative to warmest or wettest. Regional divisions are Ecoprovinces. Panel **(d)** depicts snow water equivalent as a percentage of normal.*

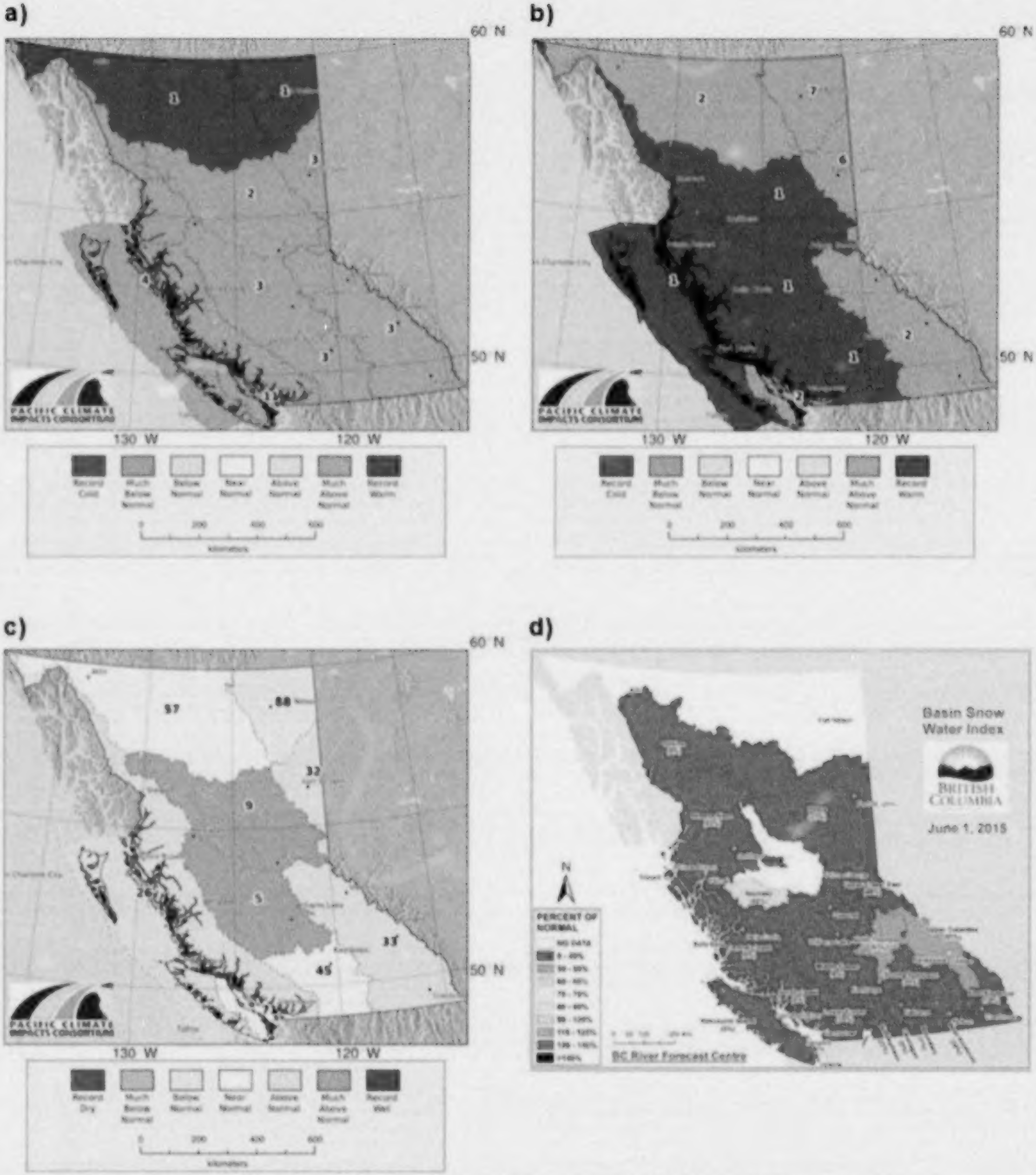
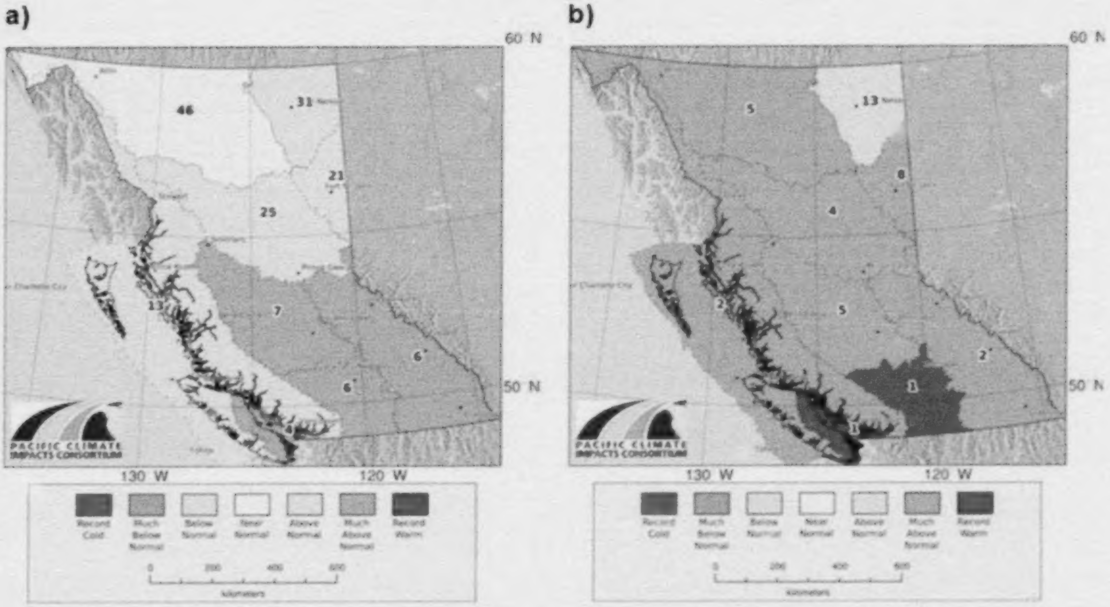

a)
b)
c)
d)
60 N
50 N
130 W
120 W
Record Cold
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warm
Record Dry
Record Wet
kilometers
97
88
32
9
5
33
45
Basin Snow Water Index
BRITISH COLUMBIA
June 1, 2015
N
PERCENT OF NORMAL
NO DATA
BC River Forecast Centre

Figure 5-2. Panels ***(a), (b), and (c)*** *depict spring (March, April and May 2015) temperature and precipitation anomalies colorized by ranking among the 116 years of data from 1900 through 2015. Minimum temperature is shown in panel* ***(a)****, maximum temperature in panel* ***(b)****, and precipitation in panel* ***(c)****. Colour classification is such that Near Normal corresponds to the 33rd to 66th percentiles, Above Normal to the 66th through 90th percentiles, Much Above Normal to 90th to all but the record year. The final category is for record which is the 99.2 percentile. Analogous categories for the below normal values are 33rd to 10th, 10th to 0.8 and record for Below Normal, Much Below Normal and Record respectively. Numbers indicate ranking relative to warmest or wettest. Regional divisions are Ecoprovinces. Panel* ***(d)*** *depicts snow water equivalent as a percentage of normal.*


a)
60 N
46
31
21
25
7
6
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13
50 N
PACIFIC CLIMATE IMPACTS CONSORTIUM
130 W
120 W
Record Cold
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warm
0
200
400
600
Kilometers
b)
60 N
5
13
8
4
5
2
2
1
1
50 N
PACIFIC CLIMATE IMPACTS CONSORTIUM
130 W
120 W
Record Cold
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warm
0
200
400
600
Kilometers

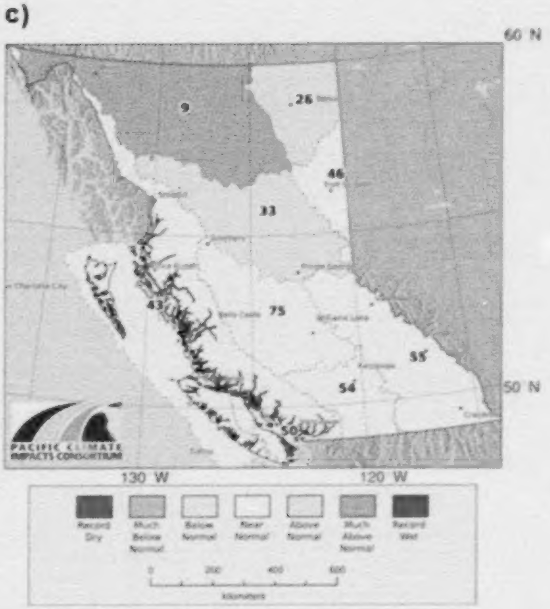
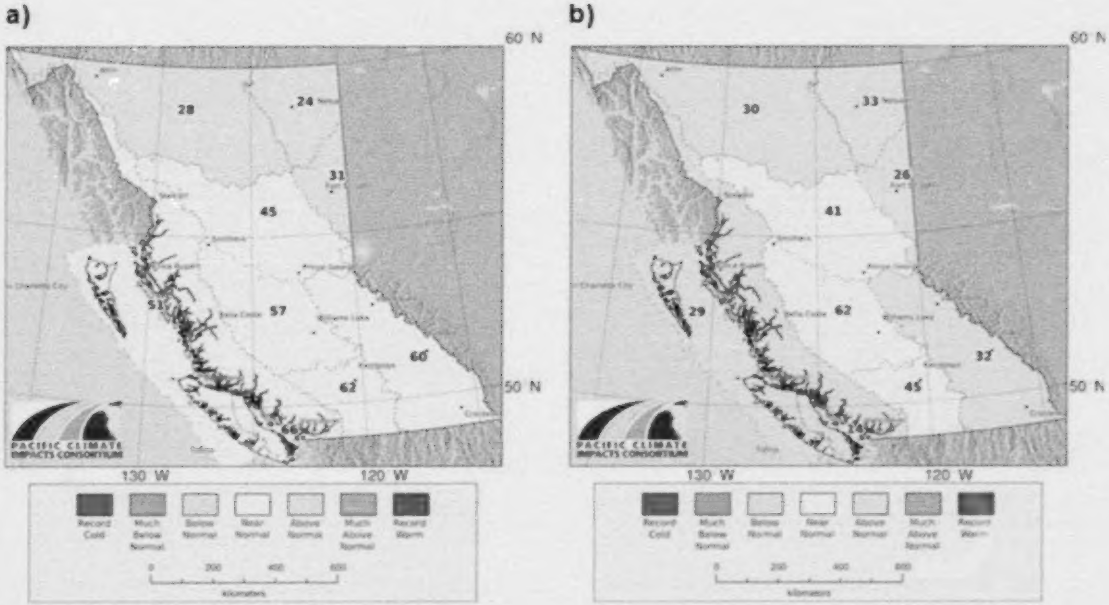

c)
60 N
9
26
46
33
43
75
55
54
50
50 N
PACIFIC CLIMATE IMPACTS CONSORTIUM
130 W
120 W
Record Dry
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Wet
0
200
400
600
Kilometers

*Figure 5-3. Panels **(a), (b), and (c)** depict summer (June, July and August 2015) temperature and precipitation anomalies colorized by ranking among the 116 years of data from 1900 through 2015. Minimum temperature is shown in panel **(a)**, maximum temperature in panel **(b)**, and precipitation in panel **(c)**. Colour classification is such that Near Normal corresponds to the 33rd to 66th percentiles, Above Normal to the 66th through 90th percentiles, Much Above Normal to 90th to all but the record year. The final category is for record which is the 99.2 percentile. Analogous categories for the below normal values are 33rd to 10th, 10th to 0.8 and record for Below Normal, Much Below Normal and Record respectively. Numbers indicate ranking relative to warmest or wettest. Regional divisions are Ecoprovinces*


a)
b)
60 N
50 N
130 W
120 W
28
24
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69
30
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41
62
29
32
45
PACIFIC CLIMATE IMPACTS CONSORTIUM
Record Cold
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Warm
0
200
400
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Kilometers

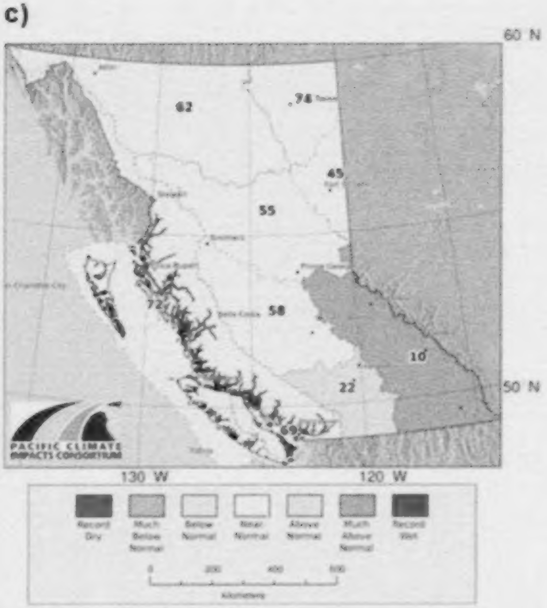
c)
60 N
50 N
130 W
120 W
62
78
45
55
58
72
10
22
69
PACIFIC CLIMATE IMPACTS CONSORTIUM
Record Dry
Much Below Normal
Below Normal
Near Normal
Above Normal
Much Above Normal
Record Wet
0
200
400
600
Kilometers

*Figure 5-4. Panels **(a), (b), and (c)** depict fall (September, October and November 2015) temperature and precipitation anomalies colorized by ranking among the 116 years of data from 1900 through 2015. Minimum temperature is shown in panel **(a)**, maximum temperature in panel **(b)**, and precipitation in panel **(c)**. Colour classification is such that Near Normal corresponds to the 33rd to 66th percentiles, Above Normal to the 66th through 90th percentiles, Much Above Normal to 90th to all but the record year. The final category is for record which is the 99.2 percentile. Analogous categories for the below normal values are 33rd to 10th, 10th to 0.8 and record for Below Normal, Much Below Normal and Record respectively. Numbers indicate ranking relative to warmest or wettest. Regional divisions are Ecoprovinces.*

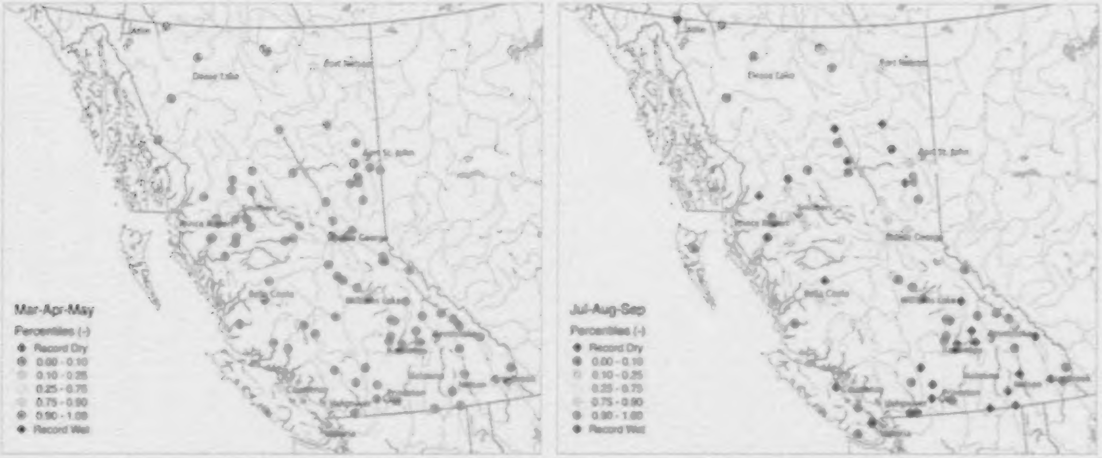
Mar-Apr-May
Percentiles (-)
Record Dry
0.00 - 0.10
0.10 - 0.25
0.25 - 0.75
0.75 - 0.90
0.90 - 1.00
Record Wet
Jul-Aug-Sep
Percentiles (-)
Record Dry
0.00 - 0.10
0.10 - 0.25
0.25 - 0.75
0.75 - 0.90
0.90 - 1.00
Record Wet

*Figure 5-5. Streamflow anomalies among the 46 years of record from 1970 to present for **a)** spring 2015 and **b)** late-summer and early-fall 2015. Rankings are in percentile as indicated in the legend and are categorically slightly different than those for temperature and precipitation. Diamond symbols indicate record high or low flows within the period of analysis.*

5.9. Conclusion

We have analysed observations of temperature, precipitation, snowpack and streamflow in British Columbia on a seasonal basis through the highly anomalous 2015 calendar year. While precipitation was near or above normal for most regions and most seasons, temperature was much above normal to record breaking during winter, spring and summer. The B.C.-wide annual average temperature was record setting. However fall 2015 was near normal in most respects across the province. The temperature and precipitation conditions resulted in a rapid loss of accumulated snow and much lower than normal snowpacks by late spring for most of B.C. The hydrological impacts of this sequence included higher than normal streamflows in spring followed by lower than normal flows in summer and early fall with some streams attaining record low levels within the period from 1970 to 2015. These effects align with expectations for hydrological conditions under climate change scenarios.

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6. WIND-DRIVEN UPWELLING/DOWNWELLING ALONG THE NORTHWEST COAST OF NORTH AMERICA: TIMING AND MAGNITUDE

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6.1. Highlights

- The time of the Spring Transition in 2015 was near the historical (1980-2015) average, which suggests that the onset of upwelling-based productivity was near average in 2015.
- Upwelling-favourable winds were above-average over the summer of 2015, suggesting that large-scale wind-driven upwelling-based productivity was above average in 2015.
- The winters of 2014/15 and 2015/16 experienced near average downwelling-favourable winds along the west coast of North America, indicating that the Aleutian Low and associated winter storm tracks exhibited near normal behaviour along the coast.
- Intensification of the Aleutian Low in the Gulf of Alaska, associated with the development of the strong El Niño in 2015/16, resulted in stronger-than-average surface winds that mixed the high sea-surface temperature downward, which appears to have eliminated the northeast Pacific warm anomaly (the "Blob").

6.2. Upwelling Timing: The Spring Transition

Along the northwest coast of North America, biologically productive upwelling conditions are predominant in summer, while downwelling predominates in winter. This biological productivity is primarily due to the link between surface winds in the along-shore direction and the associated cross-shore Ekman transport of near-surface waters. Due to storms associated with the Aleutian Low in the Gulf of Alaska, along-shore winds along the northwest coast of North America are predominantly poleward in winter, which leads to onshore transport of surface waters and downwelling. In summer, the North Pacific High is the dominant atmospheric circulation pattern, which results in equatorward winds, offshore surface transport, and upwelling. The shift from downwelling in winter to upwelling in summer occurs in spring when along-shore winds change from mainly poleward to mainly equatorward, and is referred to as the Spring Transition. The reverse process occurs in fall and is called the Fall Transition. The winds drive a similar seasonal cycle in the alongshore surface currents over the continental slope, which are also poleward in winter and equatorward in summer. This is illustrated in Figure 6-1 for locations near the west coast of Vancouver Island (Figure 6-2). Figure 6-1 also shows the 3-7 s spectra of seismic data measured at the Pacific Geoscience Centre and surface chlorophyll over the continental shelf along the southern half of Vancouver Island. The seismic data show the effects of non-linear storm wave interactions off the coast during winter while the chlorophyll delineate the summer upwelling season when values are high. Thus, both seismic and chlorophyll data help characterize the Spring and Fall Transition timing.

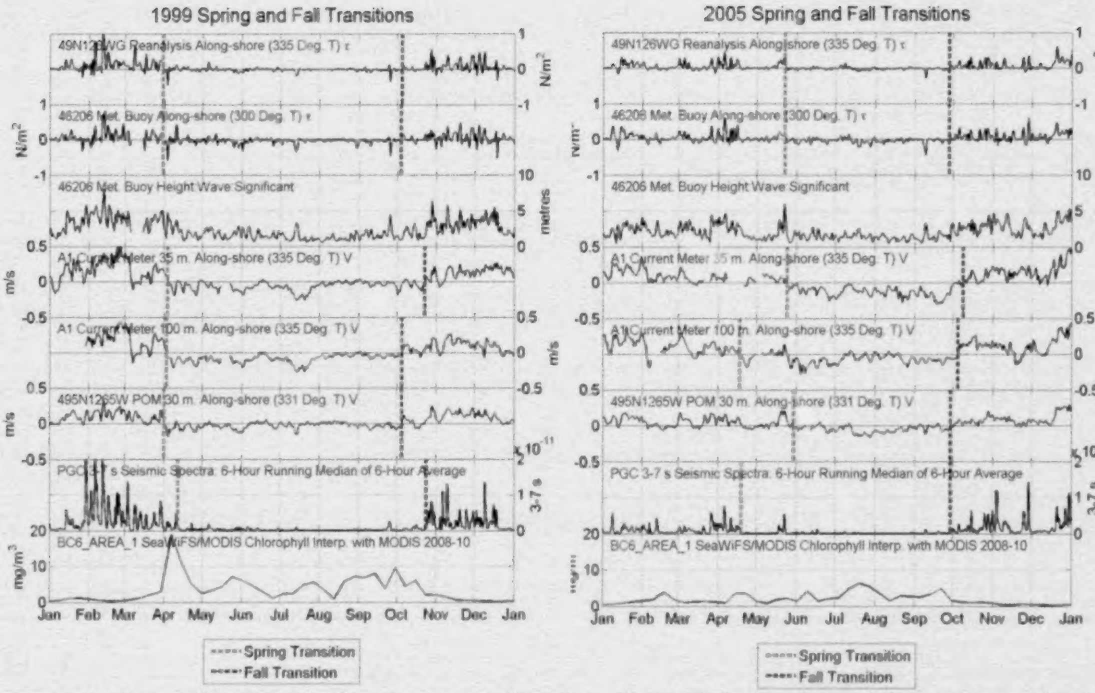


Figure 6-2. Time series depicting the Spring and Fall Transitions off the west coast of Vancouver Island in 1999 and 2005: wind stress at Reanalysis-1 grid point 49N126W and meteorological buoy 46206, significant wave height at 46206, along-shore current velocity at 35 and 100 m at mooring A1 and as modelled using the Princeton Ocean Model (POM) at 30 m (Folkes et al., 2016; Thomson et al., 2013). Positive flow is poleward (downwelling-favourable) and negative flow is equatorward (upwelling-favourable). Also shown are 3-7 s seismic spectra (Thomson et al., 2014) and satellite-observed surface chlorophyll over the continental shelf from Estevan Point to Juan de Fuca Strait (L. Brown and G. Borstad, personal communication). Vertical dashed lines show derived transition times. The late Spring Transition in 2005 was associated with depressed chlorophyll and generally poor productivity.

The timing of the spring transition and onset of seasonal upwelling varies from year to year (Thomson et al. 2014). In years such as 2005 and 2010, when the spring transition was relatively late (Figure 6-1, right panel), marine coastal productivity across trophic levels from plankton to fish to birds was generally average to below average, and was particularly poor in 2005 (DFO 2006). In years when the spring transition timing was average to early, such as 1999 and 2014, productivity was generally average to above average (e.g. see Chandler et al. 2015, reports on outer British Columbia). In 2015, the Spring Transition timing was near average, suggesting upwelling-based spring productivity was also about average.

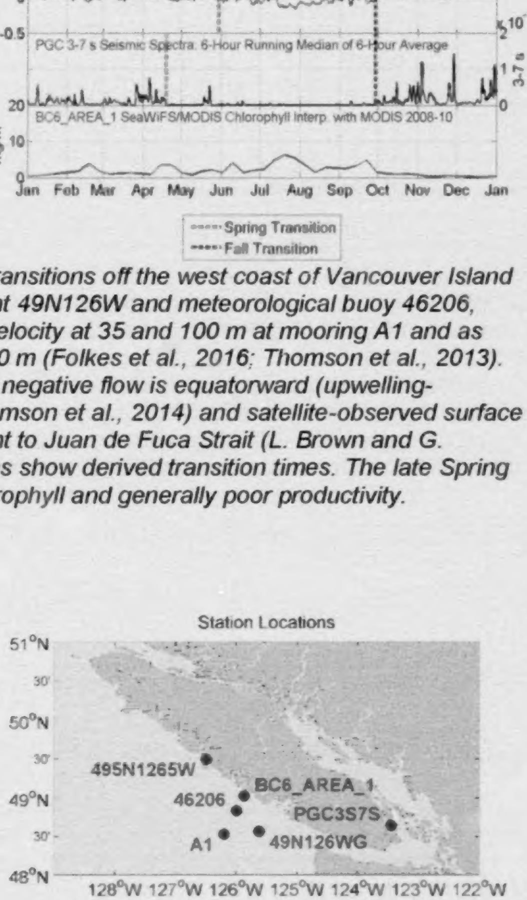


Figure 6-1. Locations of meteorological buoy 46206, current meter mooring A1, Reanalysis-1 49N126WG grid point, POM 495N1265W grid point, PGC seismic spectra, and BC6_AREA_1 chlorophyll (location depicts near the centre of the area averaged).

6.3. Upwelling Magnitude: The Upwelling Index

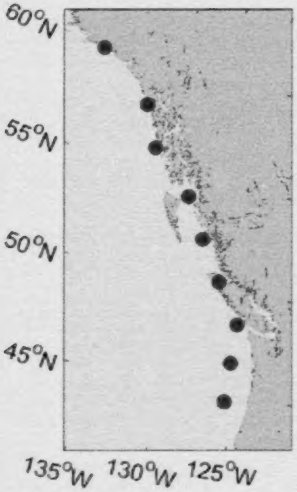


Figure 6-3. NCEP/NCAR Reanalysis-1 coastal surface wind stress grid locations.

Because they drive offshore surface Ekman transport and compensating onshore transport at depth, the duration and intensity of upwelling-favourable (northwesterly) winds are considered indicators of coastal productivity. To gauge low-frequency variability in coastal productivity, we have summed upwelling-favourable-only wind stresses by month along the west coast of North America from 45°-60° N latitude (Figure 6-3) using the NCEP/NCAR Reanalysis-1 analyses (Kistler et al., 2001). Figure 6-4 shows the monthly mean integrated upwelling anomalies smoothed using a five-year running mean over the period 1948-2015. The "regime shift" in the late 1970s (Peterson and Schwing 2003, Hare and Mantua 2000) appears as a sharp transition from stronger to weaker-than-average upwelling-favourable winds. Upwelling-favourable winds have been stronger than average throughout the 2000s. In previous State of the Pacific Ocean Reports (e.g. Irvine and Crawford 2013), we speculated that a repeat of the mid-1970s regime shift to weaker-than-average upwelling appeared imminent. Indeed, Figure 6-4 indicates a weakening to near-average upwelling conditions around 2010. However, an examination of the unsmoothed upwelling series reveals that stronger-than-average upwelling-favourable winds occurred at some time in each year between 2010 and 2015, except 2014, which was generally below average (Figure 6-5). During 2015, upwelling-favourable wind stress was above average, with positive anomalies occurring all summer. As a consequence, conditions were favourable for large-scale upwelling-based productivity to have been above average.

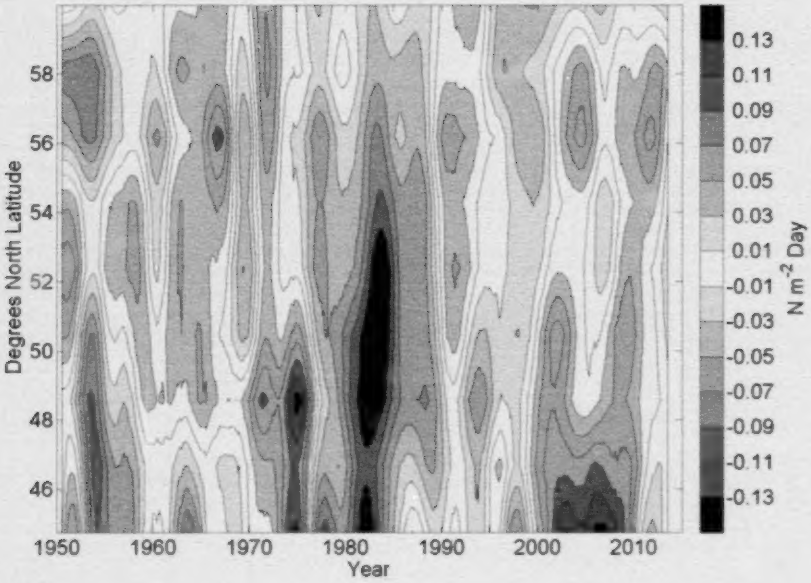


Figure 6-4. Five-year running means of monthly mean anomalies of monthly sums of alongshore upwelling-favourable (equatorward) wind stress at coastal grid points from 45-60° N.

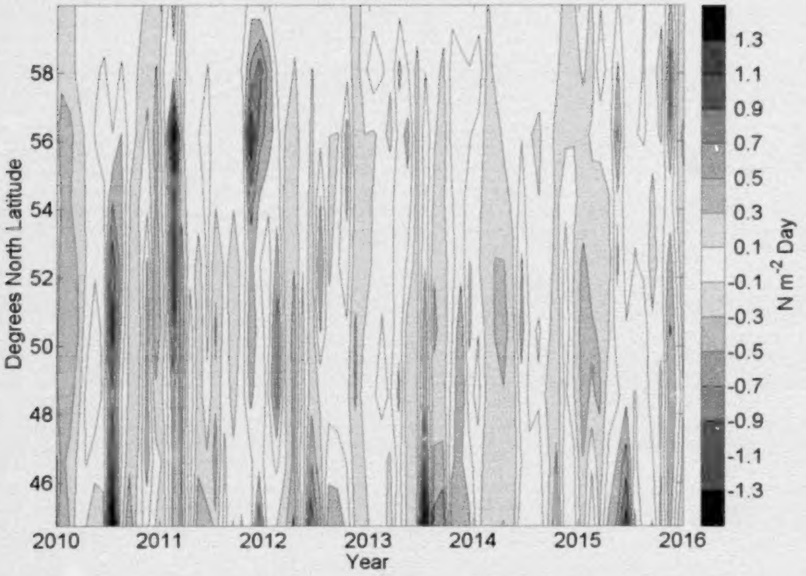


Figure 6-5. Recent (2010 to 2015) non-filtered monthly mean anomalies of monthly sums of alongshore upwelling-favourable (equatorward) wind stress at coastal grid points from 45-60° N.

6.4. Downwelling Magnitude: The Downwelling Index

We examined downwelling-favourable winds by considering only the poleward component of the alongshore wind stress; anomalies of the monthly poleward sums are shown in Figure 6-6. Here, the regime shift in the late 1970s is characterized by a latitude-dependent transition. Southward of 48º N, the transition is to weaker downwelling (shifting from average to below-average), whereas northward of this latitude the transition is to stronger downwelling (changing from below average to stronger than average). The major El Niños of 1982/83 and 1997/98 are characterized by stronger than average downwelling throughout their duration. The anomalies of largest magnitude and greatest spatial extent are positive and occurred from 1998 to 2012 over a latitude range from 45-60º N. After 2012, there was a sharp transition to weaker than average downwelling-favourable winds. A more detailed examination of the last six years (Figure 6-7) using unfiltered time series shows wintertime downwelling-favourable wind stress anomalies were stronger than average through the winters of 2009/10 through 2011/12. The winters of 2012/13 and 2013/14 experienced much weaker than average downwelling-favourable winds – these conditions led to the development and persistence of the large warm anomaly in the Northeast Pacific (Bond et al. 2015) and influenced coastal upwelling-based productivity (Chandler et al. 2015).

As indicated by Figure 6-7, the downwelling index reaches its highest magnitude during winter when storms are strongest and most frequent. Stronger than average downwelling-favourable winds during the winters of 2006/07 and 2009/10 were due to an eastward shift of the Aleutian Low and associated storm tracks. In 2009/10, stronger downwelling-favourable winds were also due to a more intense Aleutian Low. Thus, variations in the downwelling index are due to variability in the Aleutian Low, consisting of a combination of east-west shifts of the centre of the Low and variations in its strength and associated storm tracks. An eastward shift and/or intensification of the Aleutian Low leads to stronger than average downwelling, while a westward shift and/or weaker Aleutian Low leads to weaker than average downwelling. Over the winters of 2012/13 and 2013/14, downwelling-favourable winds were far below average due to a much weaker Aleutian Low, while conditions were average to stronger-than-average over the 2014/15 winter (see also Dewey 2015). Downwelling-favourable winds were about average over the early part of winter 2015/16, indicating that the Aleutian Low and associated winter storm tracks exhibited near normal behaviour along the coast.

Both upwelling and downwelling indices are positive through much of the 2000s (Figure 6-4 and Figure 6-6) due to overall increases in wind speed (wind stress), regardless of wind direction. This may be due to overall shifts in the locations and/or strength of the dominant surface wind circulation patterns in winter and summer (Aleutian Low and North Pacific High, respectively). While upwelling and alongshore advection are dependent on the wind direction, the effects on mixed-layer depth and Ekman pumping by the generally positive wind stress curl in the Gulf of Alaska in winter are mainly related to wind strength. In the short-term, variations in the surface wind circulation patterns were likely a factor in setting up the large positive sea surface temperature (SST) anomalies in the Gulf of Alaska in 2014 (Freeland 2015). However, the long-term effects in the northeast Pacific of changes in scalar wind properties is unclear, but could impact overall productivity.

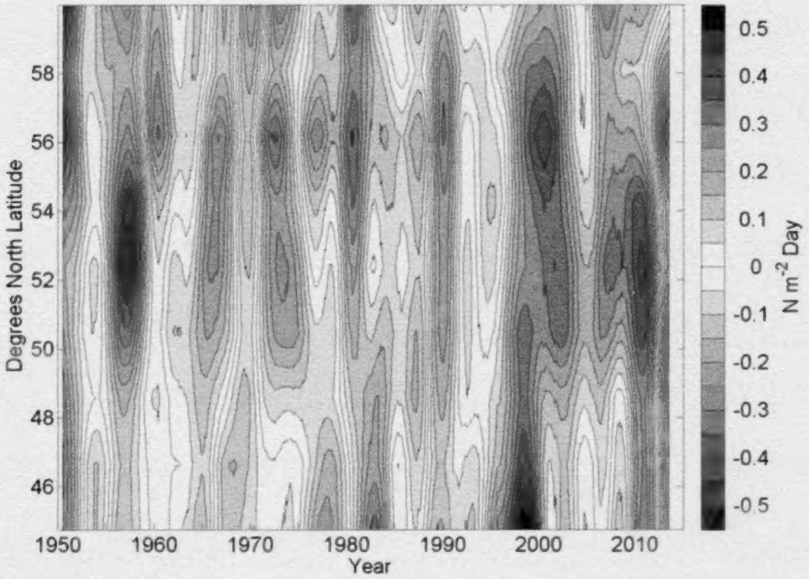


Figure 6-6. Five-year running means of monthly mean anomalies of monthly sums of alongshore downwelling-favourable (poleward) wind stress at coastal grid points from 45-60° N.

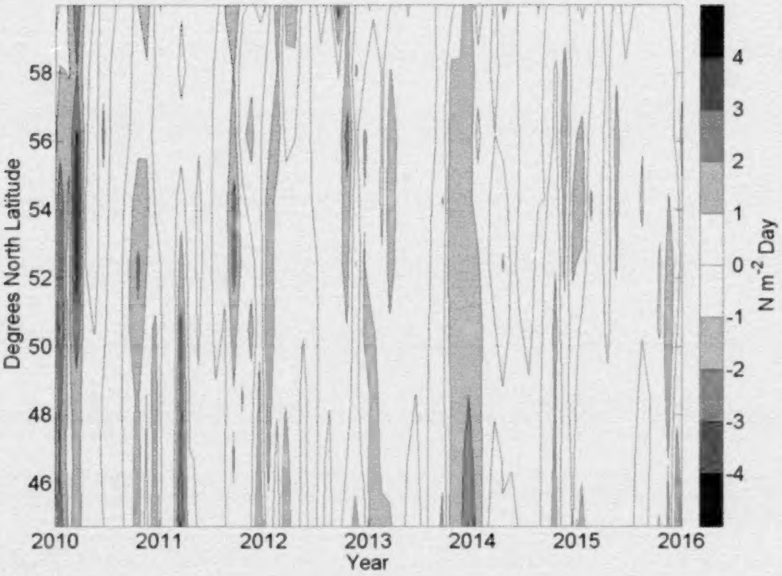


Figure 6-7. Recent (2010 to 2015) non-filtered monthly mean anomalies of monthly sums of alongshore downwelling-favourable (poleward) wind stress at coastal grid points from 45-60° N.

6.5. The Northeast Pacific Warm Anomaly: El Niño vs. The Blob

As described previously, development of the large-scale persistent warm anomaly in the northeast Pacific (the "Blob") was driven by a weaker than average Aleutian Low over the winters of 2012/13 and 2013/14. Weaker prevailing winds and/or less intense storms led to less wind-driven vertical mixing of surface waters that had been warmed during the previous summer. This is illustrated by the October 2013 positive sea-level pressure and SST anomalies in the northeast Pacific in Figure 6-8. In contrast to 2012/13 and 2013/14, the winter-time anomaly pattern accompanying El Niño events is typically manifested as an intensified Aleutian Low and negative sea-level pressure and sea-surface temperature anomalies in the Gulf of Alaska. A strong El Niño event was predicted for 2015 by NOAA's Climate Prediction Center/NCEP/NWS (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/) and in the fall of 2015 the El Niño anomaly pattern established itself over the Blob anomaly pattern (Figure 6-9). The surface warm anomaly in the northeast Pacific was gone by January 2016 (Figure 6-10).

6.6. Acknowledgements

Princeton Ocean Model (POM) current velocities were provided by Scott Tinis. Seismic data were provided by Martin Heesemann while SeaWiFS/MODIS satellite chlorophyll data were provided by Leslie Brown and Gary Borstad. NCEP/NCAR Reanalysis-1 wind stress and sea-level pressure, as well as NOAA Optimum Interpolation (OI) Sea Surface Temperature (SST) V2 provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/.

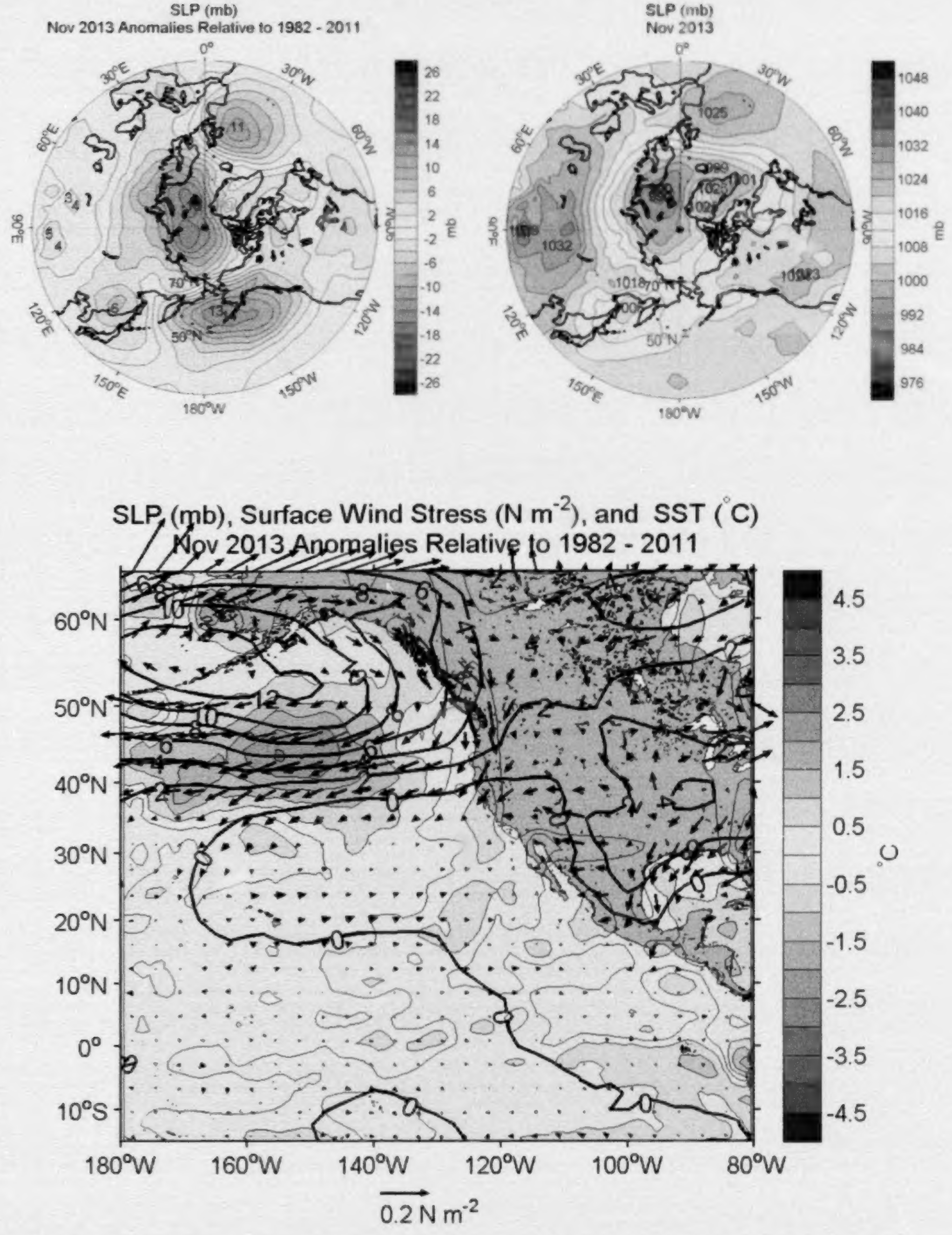
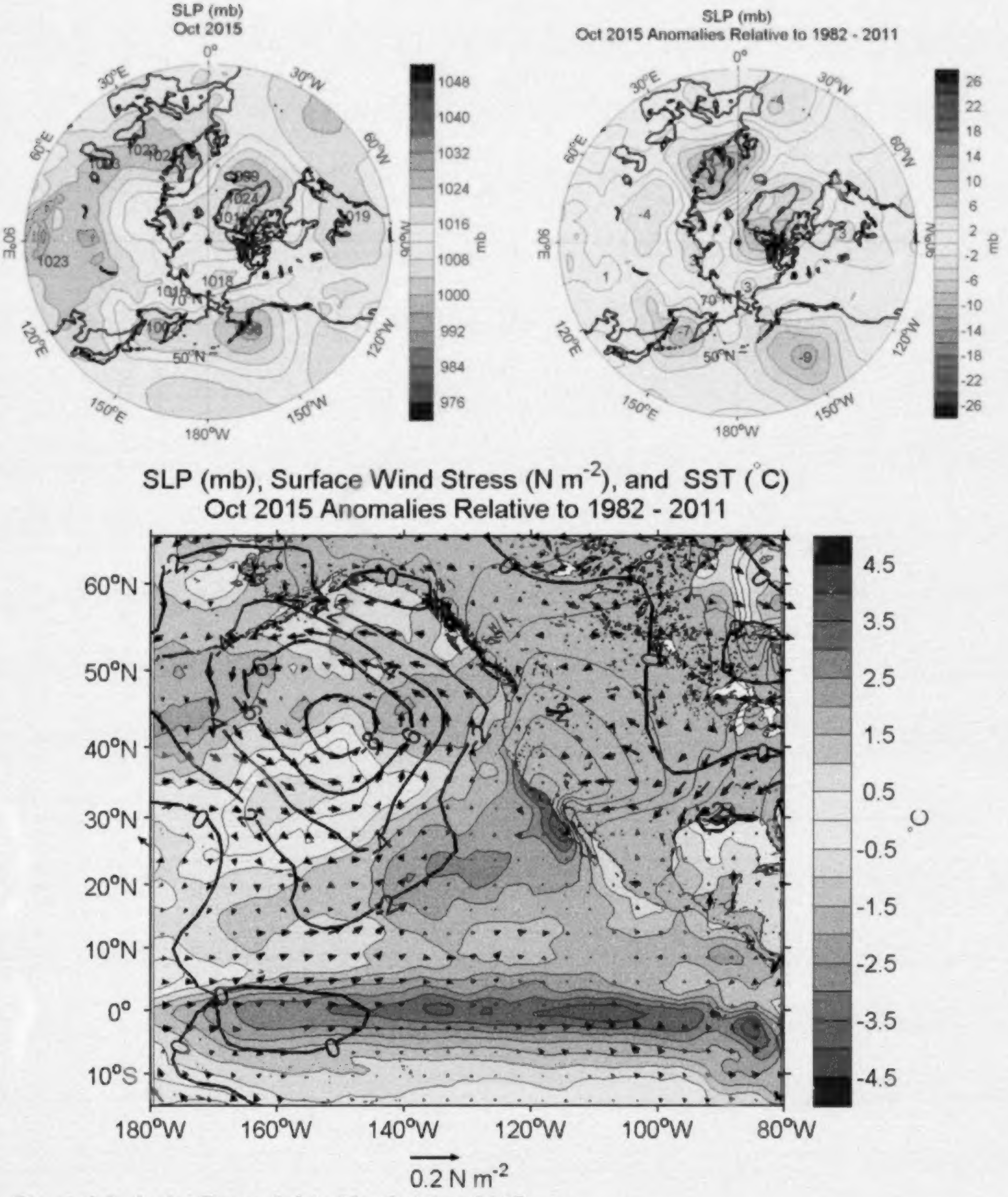

SLP (mb)
Nov 2013 Anomalies Relative to 1982 - 2011
0°
30°E
30°W
60°E
60°W
90°E
90°W
120°E
120°W
150°E
150°W
180°W
70°N
50°N
26
22
18
14
10
6
2
-2
-6
-10
-14
-18
-22
-26
mb
SLP (mb)
Nov 2013
1025
1032
1048
1040
1032
1024
1016
1008
1000
992
984
976
SLP (mb), Surface Wind Stress (N m-2), and SST (°C)
Nov 2013 Anomalies Relative to 1982 - 2011
60°N
50°N
40°N
30°N
20°N
10°N
0°
10°S
180°W
160°W
140°W
120°W
100°W
80°W
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5
°C
0.2 N m-2

Figure 6-8. Monthly mean atmospheric and SST conditions for November 2013. Top left panel: sea-level pressure (SLP); top right panel: SLP anomalies; Lower panel: anomalies of SST (colour), SLP (black contour lines), and wind stress (vectors).

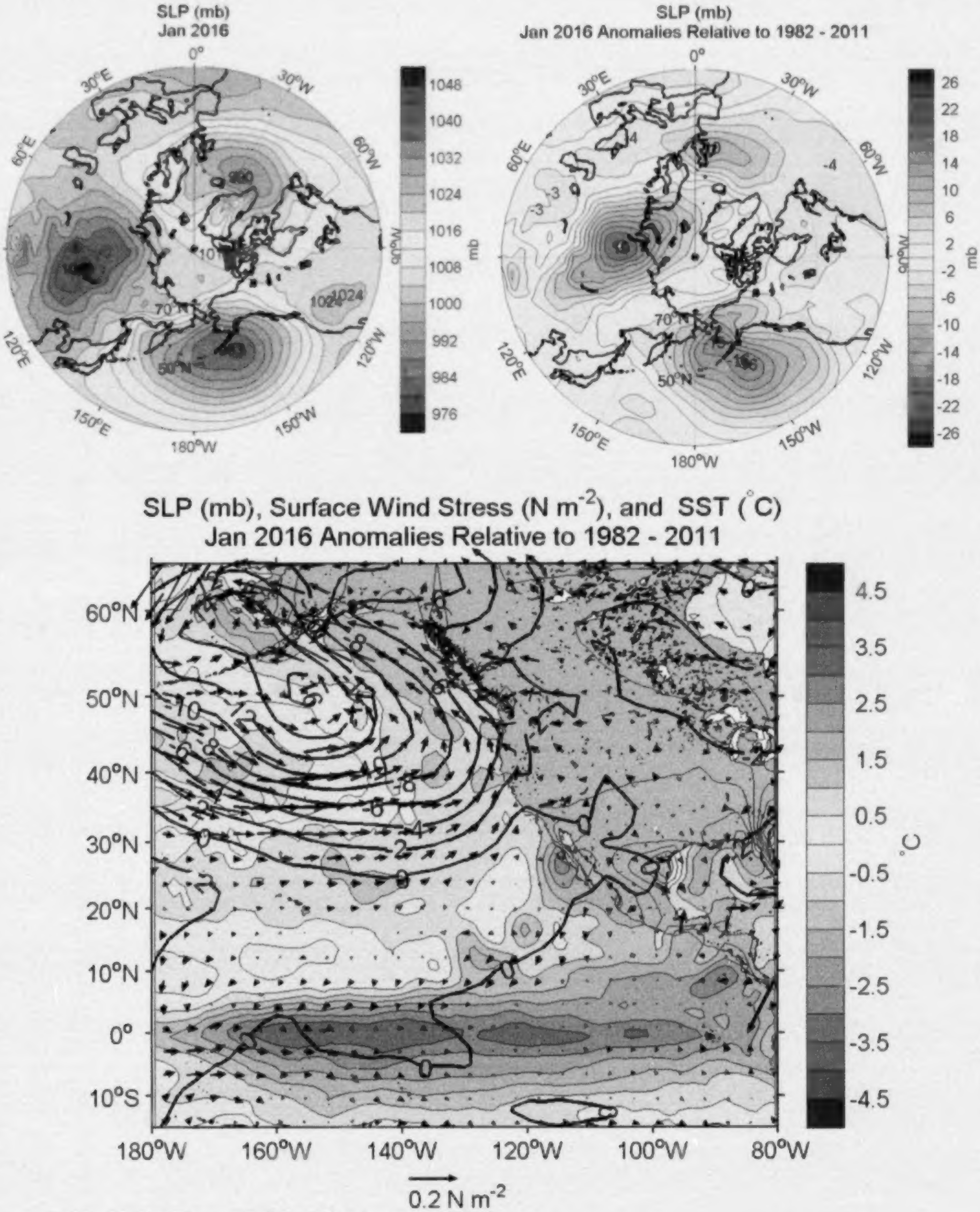

SLP (mb)
Oct 2015

SLP (mb)
Oct 2015 Anomalies Relative to 1982 - 2011

SLP (mb), Surface Wind Stress (N m^{-2}), and SST (°C)
Oct 2015 Anomalies Relative to 1982 - 2011

0°
30°E
30°W
60°E
60°W
90°E
90°W
120°E
120°W
150°E
150°W
180°W
70°N
50°N
1023
1018
1016
1019
1048
1040
1032
1024
1016
1008
1000
992
984
976
mb
-4
3
-7
-9
26
22
18
14
10
6
2
-2
-6
-10
-14
-18
-22
-26
60°N
50°N
40°N
30°N
20°N
10°N
0°
10°S
180°W
160°W
140°W
120°W
100°W
80°W
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5
°C
0.2 N m⁻²

Figure 6-9. As for Figure 6-8 but for October 2015.



SLP (mb)
Jan 2016

SLP (mb)
Jan 2016 Anomalies Relative to 1982 - 2011

SLP (mb), Surface Wind Stress (N m^{-2}), and SST (°C)
Jan 2016 Anomalies Relative to 1982 - 2011

0°
30°E
30°W
60°E
60°W
90°E
90°W
120°E
120°W
150°E
150°W
180°W
70°N
50°N
1024
1048
1040
1032
1024
1016
1008
1000
992
984
976
mb
-4
-3
26
22
18
14
10
6
2
-2
-6
-10
-14
-18
-22
-26
60°N
50°N
40°N
30°N
20°N
10°N
0°
10°S
180°W
160°W
140°W
120°W
100°W
80°W
-10
-12
-16
-8
-6
-4
-2
0
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5
°C
0.2 N m^{-2}

Figure 6-10. As for Figure 6-8 but for January 2016.

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7. SEA LEVEL IN BRITISH COLUMBIA, 1910 TO 2015

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7.1. Highlights

- Sea level is continuing to rise at Prince Rupert and Victoria.
- Changes to the trend at Tofino are due to recalibration and corrections in data from 1999 to 2012.

7.2. Summary

The Canadian Hydrographic Service monitors sea levels along the B.C. coast. The records show annual deviations from a long-term average at three ports (Figure 7-1). Both Tofino and Victoria have records that began in 1910, while the record at Prince Rupert began in 1912.

Average sea level in 2015 was above the century-long trend at Victoria and Tofino but on trend at Prince Rupert. Perhaps future analysis will explain the difference in trend between the two southern stations and Prince Rupert. The higher levels are due to warm water from the warm "Blob" (Chandler et al. 2015) and El Niño.

The linear trend at each port is (in cm/century):

Prince Rupert	+11
Victoria	+7
Tofino	-13

Tectonic motion is lifting the land at Tofino faster than sea level is rising, so that local sea level is dropping at an average rate of 13 cm per 100 years.

The next Cascadia Subduction Zone earthquake could drop the land at Tofino and along the nearby west side of Vancouver Island by as much as a metre, and also send a major tsunami to the B.C. coast.

Late in 2010 a systematic problem with independent water levels at the stations in the Canadian Hydrographic Service's Permanent Water Level Network in the Pacific. This problem had started in 1999 and was corrected station by station by mid-2011. Corrections and recalculations did not lead to significant changes to the annual mean sea level for most of the stations. However, the change at Tofino was enough to change the linear trend from -16 cm/century to -13 cm/century.

Global sea levels rose by 17± 5 cm in the 20th century. The Intergovernmental Panel on Climate Change (IPCC 2014) predicts sea level to rise by from 26 to 55 cm to 45 to 82 cm depending on levels of mitigation CO_2 emission over the 21st century, but recent observations of ice melt in Greenland and Antarctica suggest these projections might be too low. Therefore, we can expect to observe greater rates of sea level rise in British Columbia in the future than we saw in the 20th century.

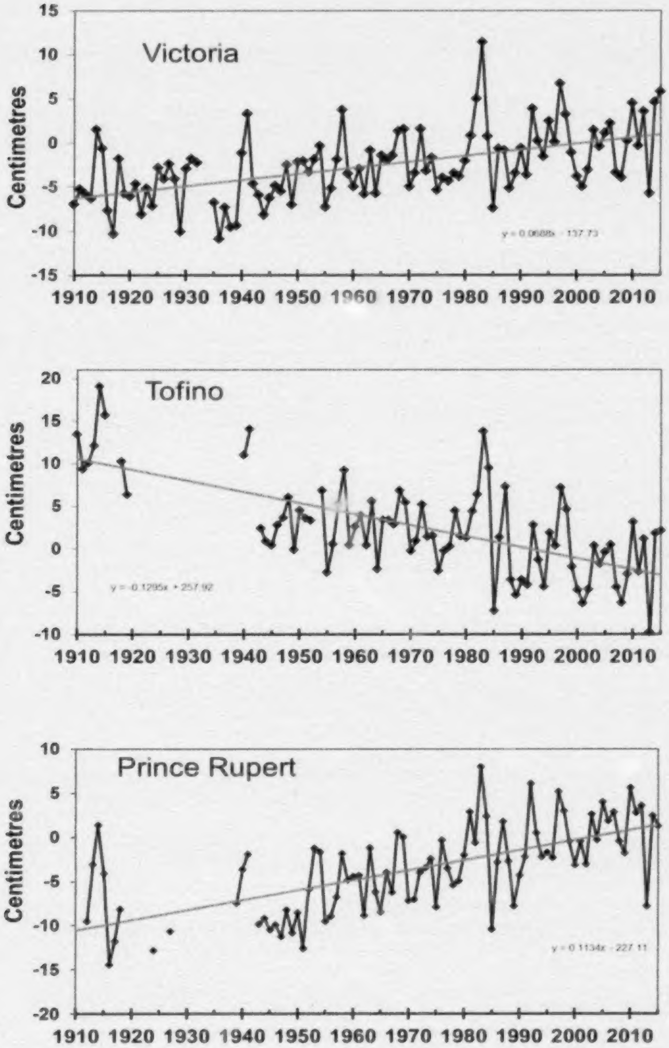

Figure 7-1.Graphs of annual-average sea level anomalies at three British Columbia ports. Reference years are 1981 to 2010. Average linear trends are plotted as red lines.

7.3. References

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8. EL NIÑO, THE BLOB AND ANOTHER WARMEST YEAR

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8.1. Highlights

- 2015 was the warmest year on record; both globally and throughout most of the Northeast Pacific.
- The warm "Blob" no longer shows up in sea surface temperature observations; however, a large temperature anomaly remains below 100 m depth.
- Stratification in the Gulf of Alaska is returning to normal, which suggests that nutrient supply in the Northeast Pacific may also return to normal.
- The 2015/16 El Niño signal is strong in the tropics, thus we should expect another warm year in 2016. A warm 2016 is also suggested by PDO, NPGO and SOI indices.

8.2. Summary

Based on NOAA data dating back to the 1880's, 2015 was the warmest year on record both globally and in much of the Northeast Pacific (Figure 8-1a). Globally, this is consistent with the recent trend, wherein the ten warmest years are nearly all in the last decade. In ranked order, the warmest years are 2015, 2014, 2010, 2013, 2005, 1998/2009 (tie), 2012, 2003/2006/2007 (tie). In the Northeast Pacific, temperatures were over 2 °C above normal (Figure 8-1b).

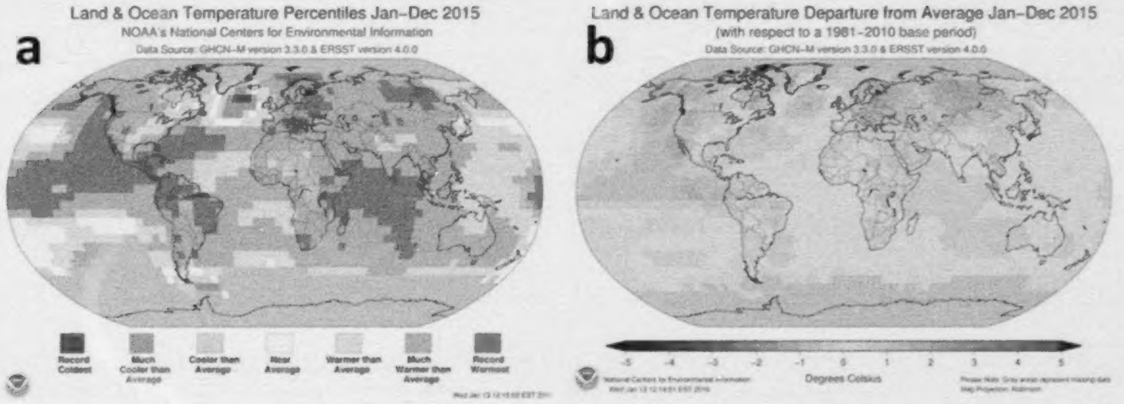
a
Land & Ocean Temperature Percentiles Jan–Dec 2015
NOAA's National Centers for Environmental Information
Data Source: GHCN-M version 3.3.0 & ERSST version 4.0.0
Record Coldest
Much Cooler than Average
Cooler than Average
Near Average
Warmer than Average
Much Warmer than Average
Record Warmest
b
Land & Ocean Temperature Departure from Average Jan–Dec 2015
(with respect to a 1981–2010 base period)
Data Source: GHCN-M version 3.3.0 & ERSST version 4.0.0
-5
-4
-3
-2
-1
0
1
2
3
4
5
Degrees Celsius

Figure 8-1. Map of the globe showing surface temperature percentiles (panel a) and anomalies (panel b) in the year 2015. ***Panel a:*** *Colours indicate percentiles, with much warmer/cooler indicating the top and bottom 10%. Source: http://www.ncdc.noaa.gov/sotc/service/global/map-percentile-mntp/201501-201512.gif.* ***Panel b:*** *Colour bar shows the temperature anomaly scale, with warm colours for relatively warm regions and cool colours for relatively cool regions. Source: http://www.ncdc.noaa.gov/sotc/service/global/map-blended-mntp/201501-201512.gif.* ***Both panels:*** *Grey areas represent missing data.*

The sea surface temperatures in the Northeast Pacific throughout 2015 (Figure 8-2) show the gradual disappearance of the strong temperature anomaly (the warm "Blob") that was observed throughout 2014. In the winter of 2015 (Figure 8-2a) the strongest temperature anomaly was along the west coast of North America, consistent with the Blob having moved onto the shelf in the late autumn of 2014 (Crawford 2015, Freeland 2015). The disappearance of the Blob from sea surface temperatures is clearest in the difference in winter time (Jan-Feb-Mar) sea surface temperatures between 2016 and 2015 (Figure 8-3). There is a large negative difference in the Northeast Pacific ocean because the surface temperatures, while still not cooler than average, were much cooler in winter of 2016 than in the winter of 2015.

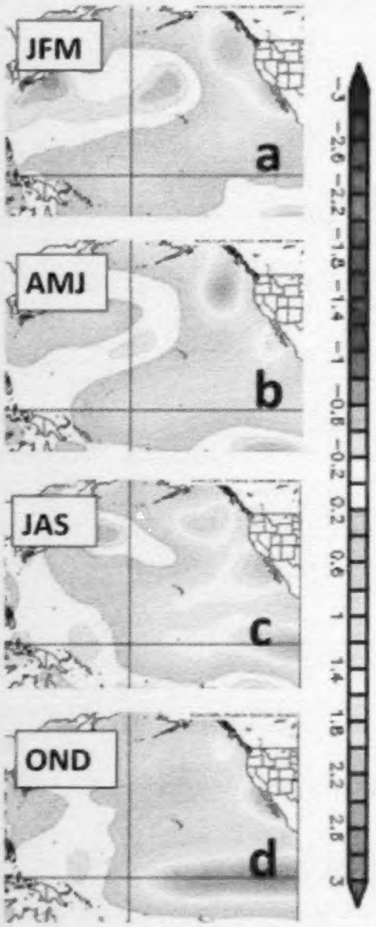
JFM
a
AMJ
b
JAS
c
OND
d
-3 -2.6 -2.2 -1.8 -1.4 -1 -0.6 -0.2 0.2 0.6 1 1.4 1.8 2.2 2.6 3

Figure 8-3. Seasonal maps of temperature anomalies in the Pacific Ocean for 2015. The colour bar on the right, showing the temperature anomaly in °C, applies to all panels. Source: NOAA Extended SST v4 *http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.*

However, while the Blob appears to have disappeared from the sea surface, a warm anomaly is still apparent at depth, based on the interpolation of Argo float data onto the location of Station Papa (Figure 8-4). Over the course of 2015, the depth of the maximum temperature anomaly has increased. It extended from the surface to 100 m depth in January 2015 and was between 100 and 150 m depth in January 2016. The deeper anomaly is more standard deviations away from the mean (over 4, rather than the earlier/shallower 3; Figure 8-4), but this is because the measured variability is smaller in the 100-150 m depth range, not because the deep temperature anomaly is larger in absolute value. As seen in Figure 8-2, the surface temperatures in late 2015 are still warmer than the long term mean (pink in Figure 8-4), but they are not warm compared with a typical warm phase of the Pacific Decadal Oscillation (i.e. 2002-2006; Figure 8-6).

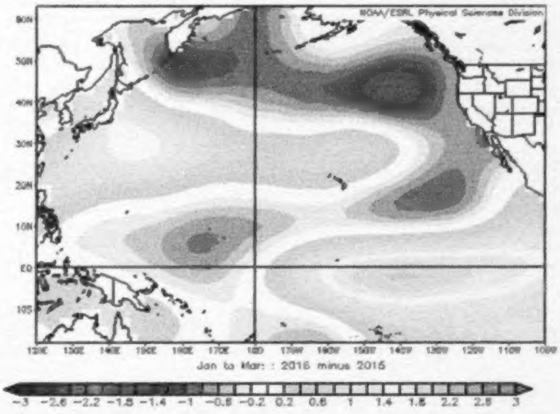
NOAA/ESRL Physical Sciences Division
60N
50N
40N
30N
20N
10N
EQ
10S
120E 130E 140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W
Jan to Mar : 2016 minus 2015
-3 -2.6 -2.2 -1.8 -1.4 -1 -0.6 -0.2 0.2 0.6 1 1.4 1.8 2.2 2.6 3

Figure 8-2. Map of the differences between the sea surface temperatures in the Pacific Ocean averaged over Jan, Feb and Mar for 2016 minus 2015. The colour bar on the bottom shows the temperature difference in °C. Source: NOAA Extended SST v4 *http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.*

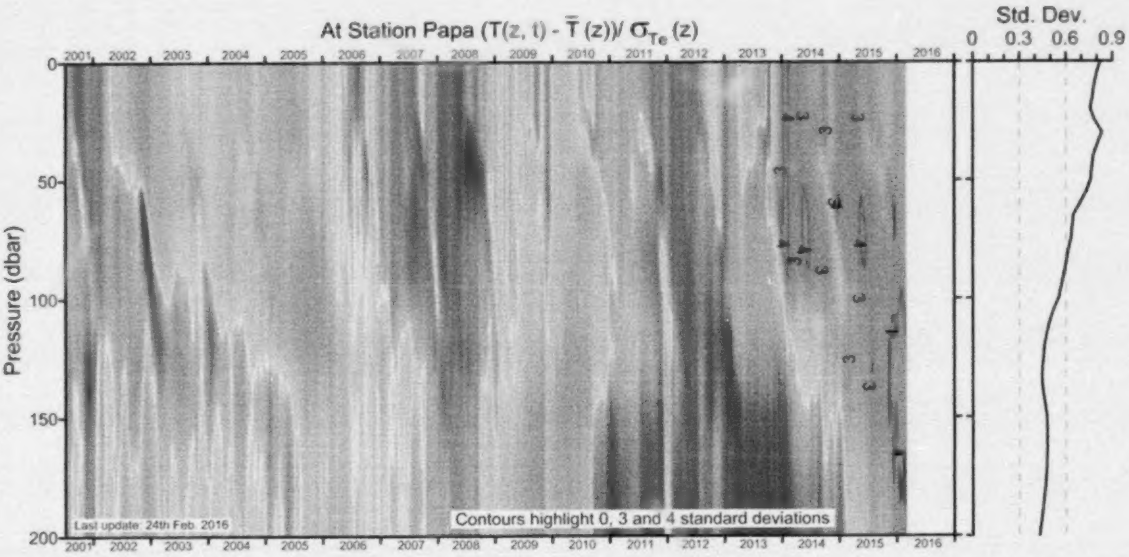

Figure 8-4. False colour plot of temperature anomalies relative to the 2001-2012 seasonally-corrected mean and standard deviation, as observed by Argo floats near Station Papa (P26: 50° N, 145° W).The cool colours indicate cooler than average temperatures and warm colours indicate warmer that average temperatures. Dark colours indicate anomalies large compared with the 2001-2012 standard deviations, which are plotted as a function of depth in the right panel (in °C).Source: Figure prepared by Howard Freeland.

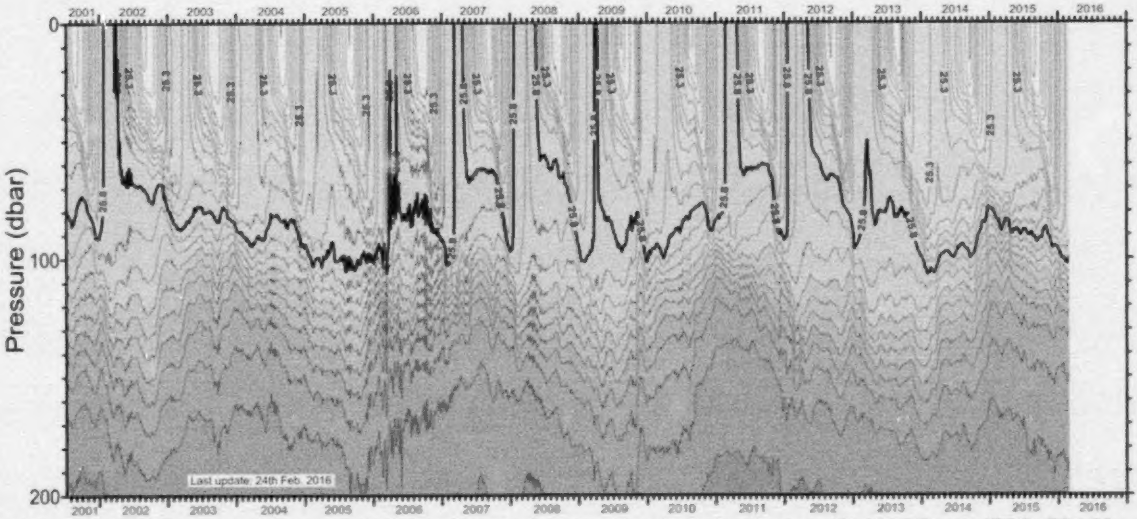

Figure 8-5. Coloured contour plot of density as observed by Argo floats near Station Papa (P26: 50° N, 145° W).The colours indicate density (pink is denser and yellow lighter). Source: Figure prepared by Howard Freeland.

After a period of stronger than usual winter stratification in the winters of 2013/14 and 2014/15 (Freeland 2015) –reduced mixing due to the Blob– the winter stratification appears to be returning to normal in the winter of 2015/16. Note that the 1025.6 kg/m^3 isopycnal reached the surface in February 2016 (Figure 8-5), which is the same as the densest isopycnal to reach the surface in the winters of 2002/03 to 2004/05. In the winters of 2013/14 and 2014/15, the densest isopycnals to reach the surface were the much lighter 1025.3 kg/m^3 (February 2014) and 1025.4 kg/m^3 (end of March 2015). Return to normal winter stratification suggests that mixing and, therefore presumably, nutrient supply from deep waters is returning to normal after the lower nutrient conditions due to the sea surface temperature anomaly (Freeland 2015).

Looking back to the sea surface temperature plots, Figure 8-3 and Figure 8-2, it is evident that as the sea surface temperature anomaly weakened in the North Pacific, a very strong anomaly appeared along the equator (Figure 8-3c and d) indicating that strong El Niño conditions were present throughout the second half of 2015 (see also the temperature increase along the equator in Figure 8-2). El Niño generally leads to warmer than average winters in western North America. It is represented by the Oceanic Niño Index (Figure 8-6) and this is only one of several indices that suggest the Northeast Pacific Ocean is currently in a warm period. In general, warming aligns with El Niño (positive ONI), positive ALPI and PDO and negative NPGO and SOI. All indices (except the ALPI, which is neutral) indicate warm conditions. As noted previously (Crawford 2015), the recent warm period follows a relatively long cool period (2007 to 2013, seen best in the PDO, NPGO and SOI indices).

8.3. Climate Indices

Aleutian Low Pressure Index (ALPI) measures the relative intensity of the Aleutian Low pressure system of the north Pacific (December through March). It is calculated as the mean area (in km²) that has sea level pressure less than or equal to 100.5 kPa and is expressed as an anomaly from the 1950-1997 mean (Surry and King 2015). A positive index value reflects a relatively strong, or intense, Aleutian Low. There is no value for 2016 yet. ALPI is provided by DFO Pacific (PBS) and is

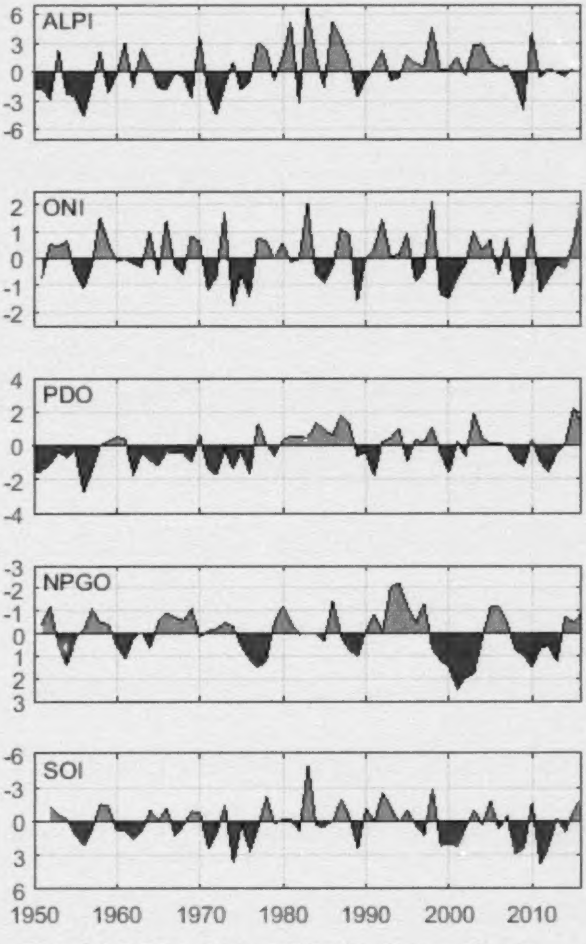

Figure 8-6. Time series of Pacific Ocean climate indices. Aside from ALPI, which is already an average, each of the monthly indices were averaged over the months of Nov, Dec, Jan and Feb and plotted for the year in Feb. Some series are inverted (negative values are above the axes) so that all series are red when coastal B.C. temperatures are anomalously warm. See text for a description and the source of each index.

available from: http://www.pac.dfo-mpo.gc.ca/science/species-especes/climatology-ie/cori-irco/alpi/index-eng.html.

The **Oceanic Niño Index (ONI)** is a monthly index which is a 3 month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region (5° N-5° S, 120°-170° W) plotted on the center month. The SST anomalies are calculated based on 30-year base periods that are updated every 5 years, which accounts for global warming and some of the decadal-scale SST variability (as seen in the PDO index). ONI is provided by the NOAA's National Weather Service National Centers for Environmental Prediction CPC and is available from: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.

The **Pacific Decadal Oscillation (PDO) Index** is defined as the leading mode of monthly sea surface temperature variability (1st PC of SST) in the North Pacific (Mantua et al. 1997, Zhang et al. 1997). It represents a long-lived El Niño-like pattern of Pacific climate variability, generally indicating warm/cool patterns that persist for a decade or more. PDO is provided by the Joint Institute for Studies of Atmosphere and Ocean of NOAA and is available from: http://research.jisao.washington.edu/pdo/.

The **North Pacific Gyre Oscillation (NPGO)** is a climate pattern that emerges as the 2nd dominant mode of sea surface height variability (2nd PC of SSH) in the Northeast Pacific. The NPGO has been shown to be significantly correlated with fluctuations of salinity, nutrients and chlorophyll-a from long-term observations in the California Current (CalCOFI) and Gulf of Alaska (Line P) (Di Lorenzo et al. 2008). Monthly values of NPGO are available from: http://www.o3d.org/npgo/.

The **Southern Oscillation Index (SOI)** is the anomaly in the sea level pressure difference between Tahiti (17°40′ S 149°25′ W) and Darwin, Australia (12°27′0″ S 130°50′0″ E). It is a measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific (i.e. the state of the Southern Oscillation) and, as it represents the changes in winds that set up El Niño/La Niña events, the ONI follows it quite closely. SOI is provided by the NOAA's National Weather Service National Centers for Environmental Prediction CPC and is available from: http://www.cpc.ncep.noaa.gov/data/indices/soi.

8.4. References

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9. SEA SURFACE TEMPERATURE AND SALINITY TRENDS OBSERVED AT LIGHTHOUSES AND WEATHER BUOYS IN BRITISH COLUMBIA, 2015

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9.1. Highlights

- Water temperatures in 2015 were warmer than normal for a second consecutive year.
- A rapid and early snowmelt introduced large volumes of fresh water into the Strait of Georgia resulting in negative salinity anomalies in the first part of the year, and positive anomalies after the summer.

9.2. Summary

Two sources of data are used to describe changes in sea surface conditions in the coastal waters of B.C. in 2015. As part of the DFO Shore Station Oceanographic Program sea surface temperature and salinity are measured daily at 12 shore stations, at the first daylight high tide. Most stations are at lighthouses (Figure 9-1), with observations taken by lighthouse keepers using a handheld electronic instrument (YSI Pro 30). The buoy data are provided by Environment Canada from a network of ODAS (Offshore Data Acquisition Systems) buoys that collect weather data hourly.

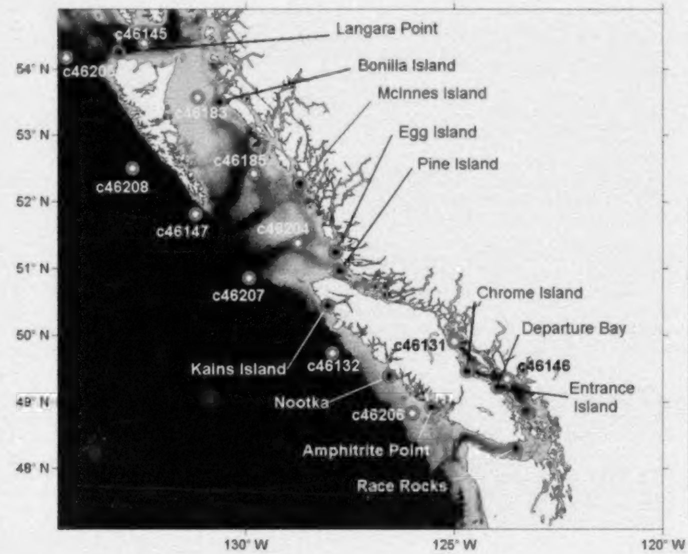
Langara Point
Bonilla Island
McInnes Island
Egg Island
Pine Island
Chrome Island
Departure Bay
Entrance Island
Kains Island
Nootka
Amphitrite Point
Race Rocks
c46145
c4620
c46183
c46185
c46208
c46147
c46204
c46207
c46132
c46131
c46146
c46206
54° N
53° N
52° N
51° N
50° N
49° N
48° N
130° W
125° W
120° W

Figure 9-1. Red dots with black centres show the locations of 12 stations in the present shore station network. Red dots with white centers show the locations of 12 weather buoys in the Canadian weather buoy network. The length of each record is shown in the table below.

Station	Years of data
Departure Bay	101
Race Rocks	94
Nootka	81
Amphitrite Pt	81
Kains I	78
Langara Pt	79
Entrance I	79
Pine I	78
McInnes I	61
Bonilla I	55
Chrome I	54
Egg I	45

Buoy ID	Buoy Location	Years of data
c46146	Halibut Bank	23
c46131	Sentry Shoal	23
c46206	La Perouse	27
c46132	South Brooks	21
c46207	East Dellwood	26
c46147	South Moresby	22
c46208	West Moresby	25
c46205	West Dixon	25
c46145	Central Dixon	24
c46204	West Sea Otter	26
c46185	South Hecate	24
c46183	North Hecate	24

The observations at the shore stations show the average daily sea surface temperature (SST) at all stations was warmer in 2015 than in 2014 (Figure 9-2; mean increase of 0.82 °C, standard deviation of 0.39 °C), and warmer in 2015 than the 30 year average, 1980-2010 (mean increase of 1.11 °C, standard deviation of 0.43 °C).

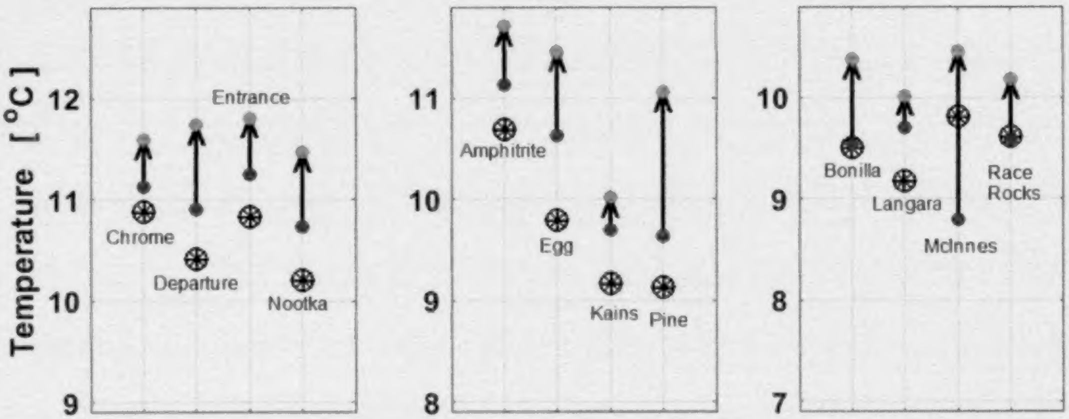

Figure 9-2. The average SST in 2014 (blue dots) and 2015 (red dots) from daily observations at shore stations along the west coast of Canada. Note: the temperature range is the same in each panel, but the temperature values vary; cooler in the left panel and warmer in the right. The crossed circles represent the mean annual temperature based on 30 years of data (1981-2010).

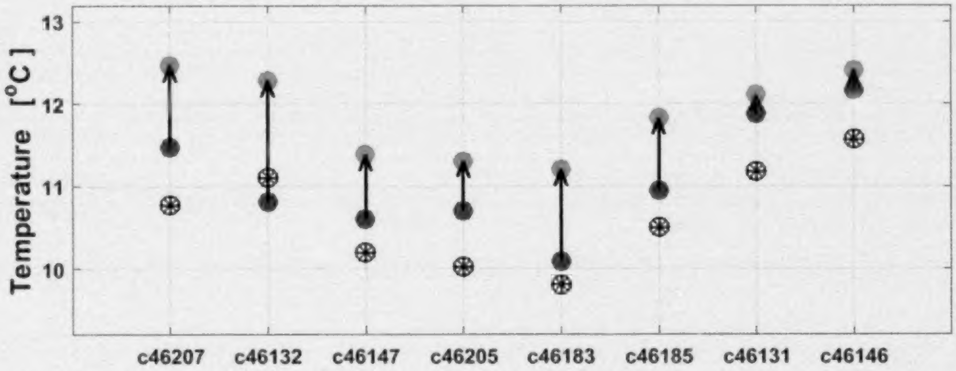

Figure 9-3. The average SST in 2014 (blue dots) and 2015 (red dots) from hourly observations at weather buoys along the west coast of Canada. Note: at four buoys there were insufficient data available to make the comparison between years. The crossed circles represent the mean annual temperature based on all years of data.

The observations from the weather buoys show the average daily SST (Figure 9-3) at all stations was warmer in 2015 than in 2014 (mean increase of 0.79 °C, standard deviation of 0.43 °C), and warmer in 2015 than in the 22 year average,1989-2010 (mean increase of 1.22 °C, standard deviation of 0.27 °C). It can be seen that the buoys located in the Strait of Georgia showed a lesser increase in SST than those on the west and central coasts of B.C.

Figure 9-4 shows the time series of SST observed at two locations off the west coast of B.C., and one in the Strait of Georgia. All demonstrate above normal temperatures for most of the year, with brief cool events attributable to upwelling or wind mixing.

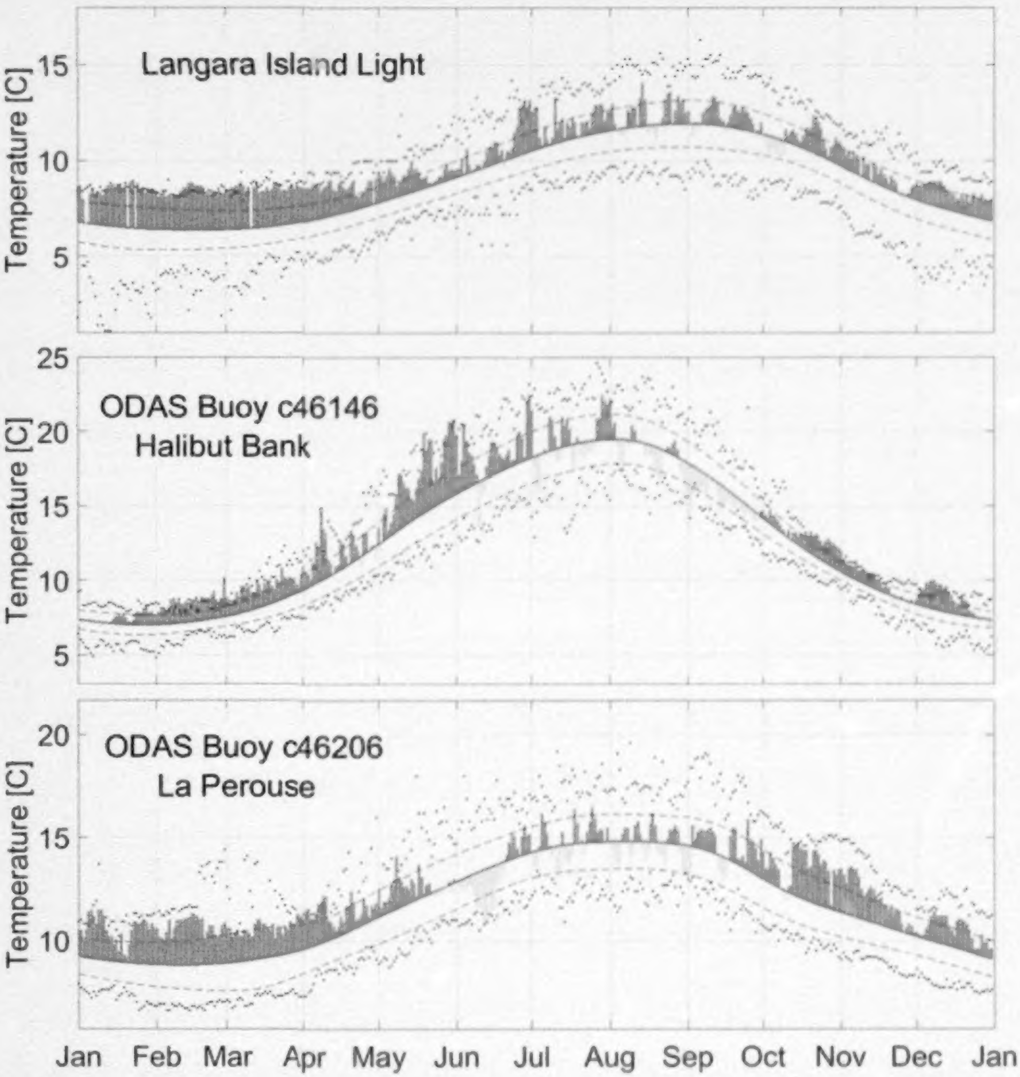

Figure 9-4. Time series of daily SST, blue areas represent temperatures that are below normal, red areas represent temperatures that are above normal. Normal means an average (blue line) of all observations and the dashed blue lines show one standard deviation from the average. The black dots show the maximum and minimum temperature observed for each day of the year.

The time series of sea surface salinity observed at Chrome Island in the Strait of Georgia presented as Figure 9-5 shows the low salinity conditions experienced during the first half of 2015 due to the rapid and early snowmelt in the coastal mountain ranges.

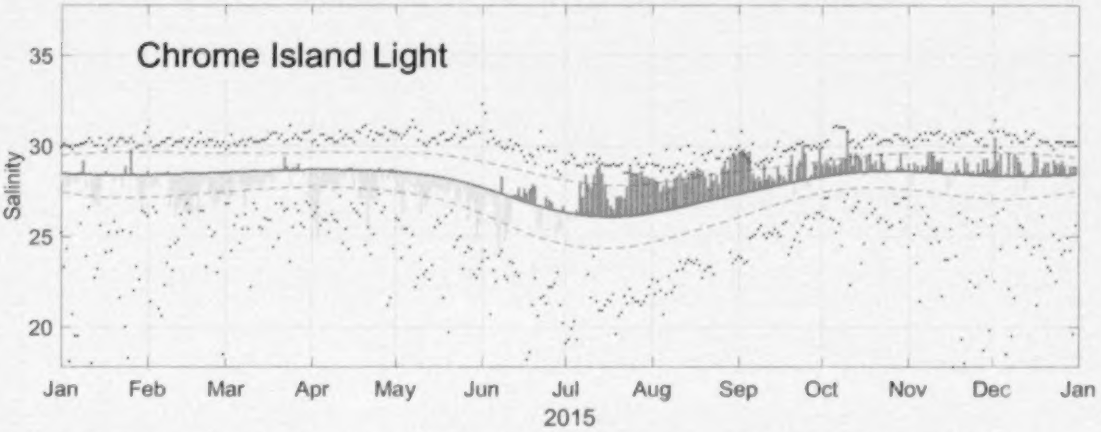

Figure 9-5. Time series of daily sea surface salinity, blue areas represent salinities that are below normal, red areas represent salinities that are above normal. Normal means an average (blue line) of all observations and the dashed blue lines the dashed blue lines show one standard deviation from the average. The black dots show the maximum and minimum salinity observed for each day of the year.

Assuming a linear change over the entire data record, the time series of temperature at all of the B.C. shore stations show a warming trend at a 95% confidence level. Figure 9-6 gives an example of this warming at representative stations for each of three regions (North and Central Coast, the west coast of Vancouver Island, and the Strait of Georgia). The right panel of Figure 9-6 shows the SST trend using data up to the year shown on the x-axis. The slope of the trend varies with time, and the 2015 conditions influence the SST trend to a faster rate of increase which, since 2005, had shown long-term warming, but at a decreasing rate. A similar trend analysis applied to the salinity data (Figure 9-7) shows a continuing long-term trend toward less saline conditions.

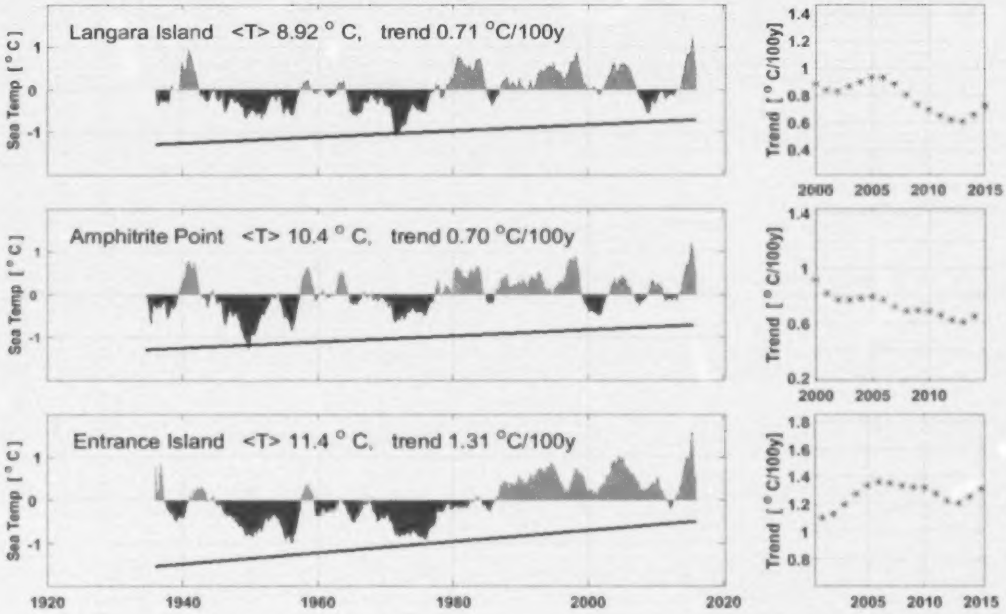

Figure 9-6. Time series of daily temperature observations, averaged over 12 months, at stations representing the North and Central Coast, west coast of Vancouver Island and Strait of Georgia. Positive anomalies from the average temperature of the entire record <T> are shown in red, negative in blue. The panel to the right shows the slope of the trend lines calculated using only data up to the year shown on the x-axis.

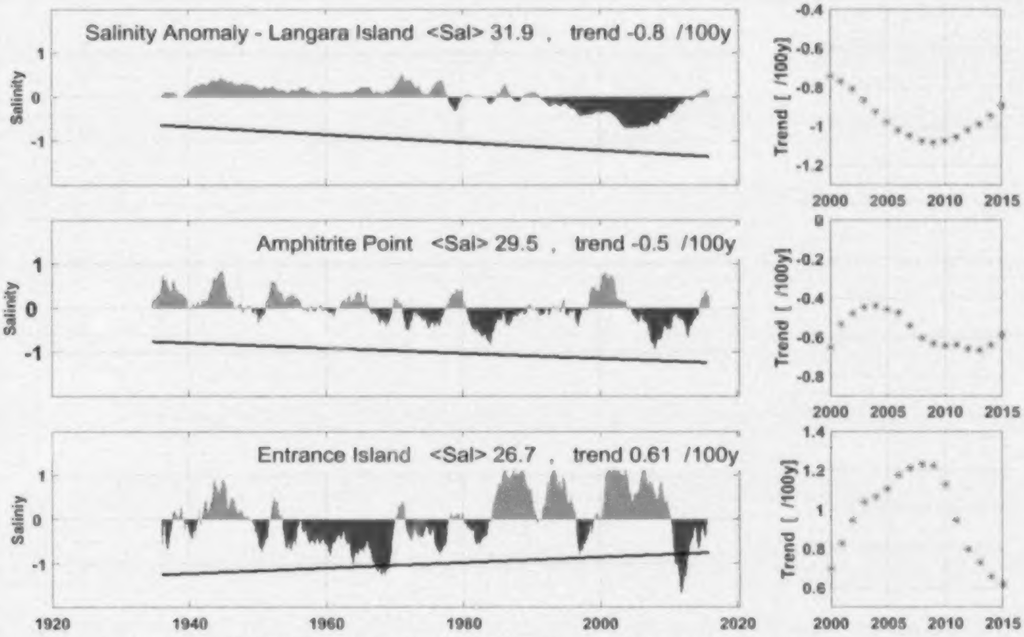

Figure 9-7. As in Figure 9-6 for long-term time series of daily salinity observations.

10. OXYGEN CONCENTRATION IN B.C. WATERS

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10.1. Highlights

- Oxygen concentration (O_2) at the bottom of the continental shelf in late summer is normally low, reaching lowest concentration off southwest Vancouver Island.
- O_2 declined from 70 µmol/kg to 30 µmol/kg from 1980 to 2009, and then increased slightly from 2010 to 2014.
- O_2 increased in August 2015 to 90 µmol/kg, attributed to the anomalously warm, oxygenated bottom water of this summer.

10.2. Oxygen concentration on the continental shelf

A detailed composite image of near-bottom oxygen concentration (O_2) is presented in Figure 10-1. Blue, red and black symbols reveal decreasing O_2 and increasing hypoxia. (Hypoxia is defined as a concentration less than 1.4 ml/L or 60 µmol/kg.) Many of these symbols are in inlets where deep seawater is naturally hypoxic due to low rates of inflow from outside waters. On the continental shelf and slope, lowest O_2 is in deeper waters because O_2 decreases with depth. Lowest O_2 at near-bottom at depths shallower than 200 m, as denoted by clusters of red symbols, is off southwest Vancouver Island, the region of the B.C. coast where summer upwelling is strongest. Decreasing O_2 in subsurface waters is normally accompanied by increasing acidity. Both trends are of great concern to marine life.

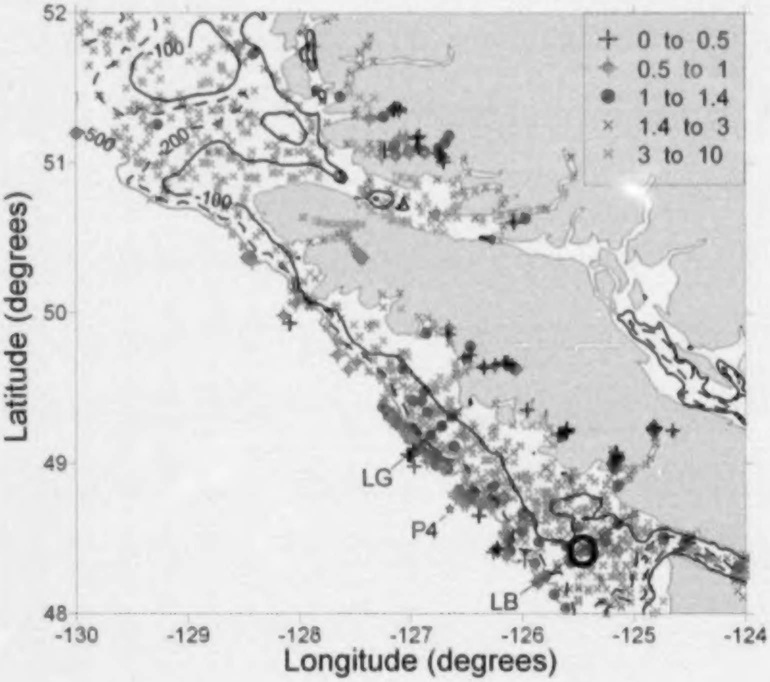

Figure 10-1. Oxygen concentration (O_2) in (ml/L) in summer within 20 metres of the ocean bottom for regions of the continental shelf and slope where bottom depth is less than 1000 metres. (1 ml/L = 43 µmol/kg) Each symbol represents a measurement by DFO research programs. A black ***O*** *denotes the location of Station LB08. Station P4 is also indicated. Source: Crawford and Peña 2013.*

Oxygen concentration in subsurface waters of the British Columbia continental shelf and slope declined from about 1980 to 2009. We monitor this decline on the shelf by measuring O_2 at Station LB08 in 145 m of water off southwest Vancouver Island (shown in Figure 10-1). The decline in O_2 since 1979 reached a minimum in 2006 to 2009 in late summer and early autumn from days 241 to 289 (Figure 10-2). This decline is also present in spring between days 120 and 160. Observations in the years 2010 to 2013 reveal somewhat higher O_2 than for the period 2006 to 2009. Even higher values of O_2 were observed in 2014 and 2015, with the highest ever late summer O_2 of 2.14 ml/L (= 92 µmol/kg) measured in early September 2015. This very high O_2 is attributed to a deep mixed layer of warm, well-oxygenated seawater.

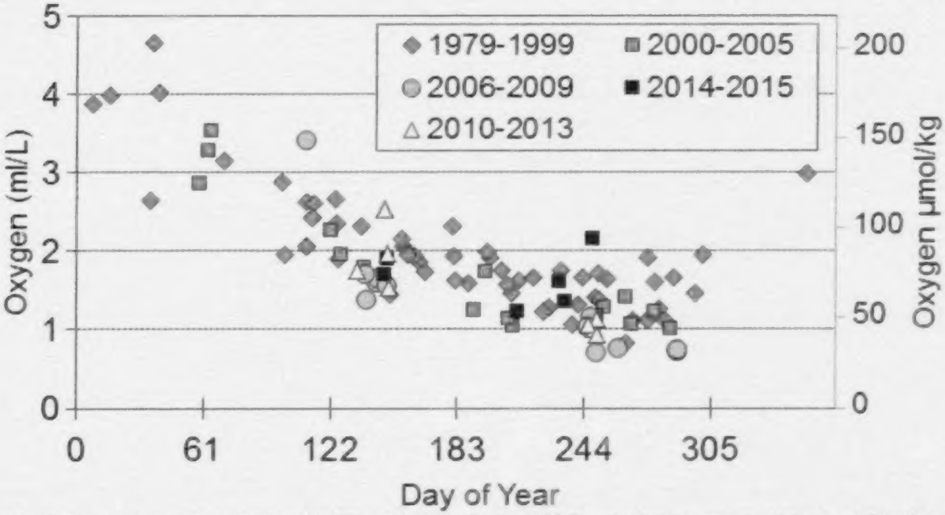

Figure 10-2. Oxygen concentration (ml/L and µmol/kg) at 125 m below ocean surface at Station LB08. The location of this station is shown in Figure 10-1. Symbols represents sampling by DFO programs, plotted on the day of the year the sample was collected. Most measurements after 2006 are provided by the La Perouse Program in spring and late summer to early autumn. Figure is based on Crawford and Peña 2013.

To show the general trend since 1979 when regular sampling began at LB08, we present in Figure 10-3 a time series from 1979 to 2015 of average O_2 observed between days 241 and 289 of each year. These are the days shown in Figure 10-2 to have lowest O_2. This graph reveals the general decrease in O_2 until 2009, and also the two highest values of O_2 in 1998 and 2015. Both these highest concentrations are in El Niño years.

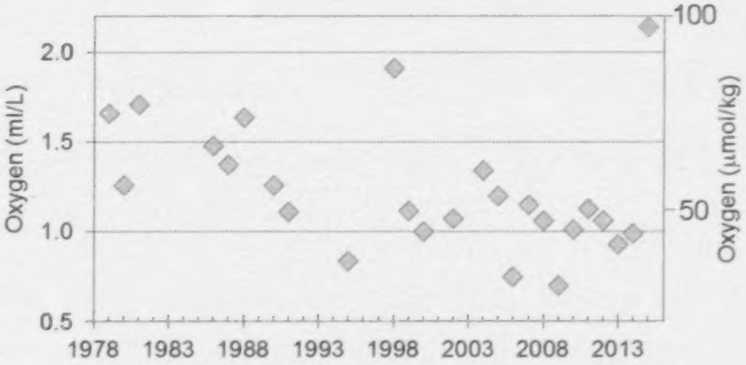

Figure 10-3. Time series of O_2 at LB08 averaged between days 241 and 289 of each year, plotted versus year of observation. Figure is based on Crawford and Peña, 2013.

10.3. Oxygen concentration on the continental slope

A second station with a long time series is located along Line P at Station P4 on the continental slope in 1300 metres of water. For this location we present in Figure 10-4 the time series of average summer O_2 at four depths below surface. The decline in O_2 from the 1980s to 2009 observed at LB08 is also present at P4 at depths of 150, 200 and 250 m, as is the increase in O_2 after 2009. There are two sets of observations in the early 1960s that reveal O_2 to be lower than in the 1980s. Little is known of the trend from 1961 to 1980 due to lack of sampling. To investigate this gap, Crawford and Peña (2016) examined all data on this continental slope from 1949 to 2012, binning observations into latitude bands rather than at a single station. Their results reveal a general increase in O_2 from the 1950s to 1980s, followed by a decrease to about 2009.

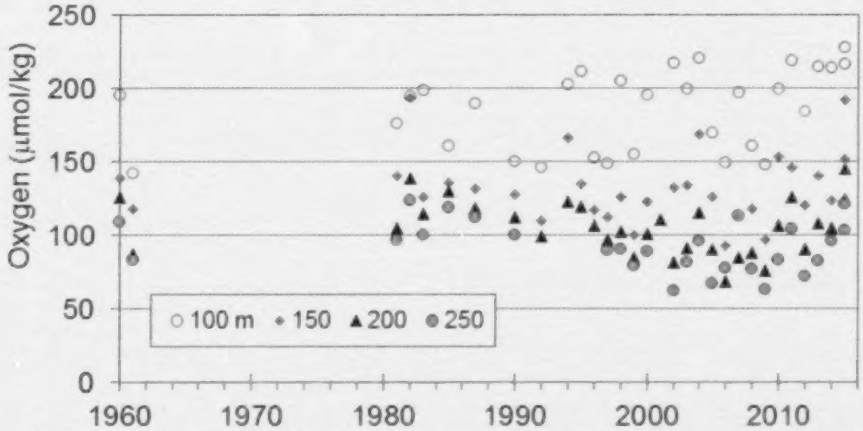

Figure 10-4. Time series of O_2 at Station P4, averaged over observations in summer. Results are presented for 4 depths below surface. Figure is based on Crawford and Peña 2013.

10.4. References

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11. 2015 CONDITIONS ALONG THE COAST OF VANCOUVER ISLAND (LA PEROUSE PROGRAM) AND LINE P

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11.1. Highlights

- The temperature anomaly in August 2015 along Line P was the highest on record and was situated at depth, therefore not visible from satellites.

11.2. Summary

The La Perouse program is a series of sampling lines on the west coast of Vancouver Island (WCVI), ranging from the mouth of the Juan de Fuca Strait in the south to Cape Scott in the north (Figure 11-1). The program started in the late 1970s and is now sampled twice per year, in late May and early September.

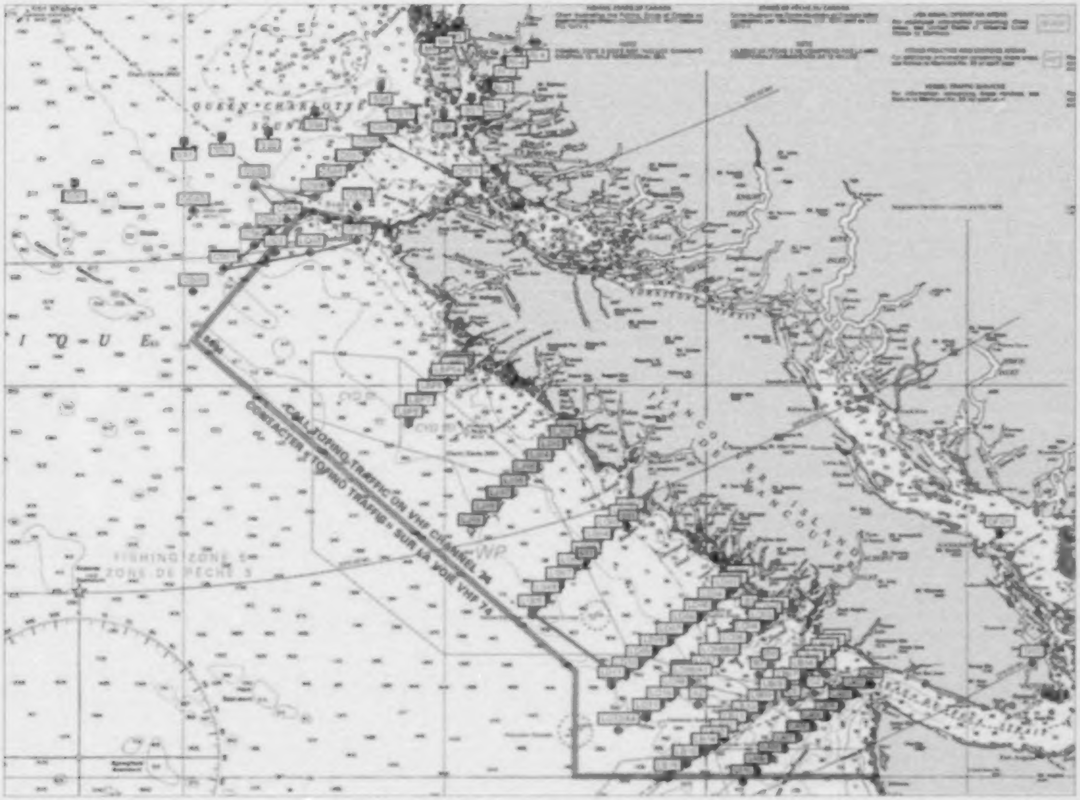
QUEEN CHARLOTTE SOUND
CALL TOFINO TRAFFIC ON VHF CHANNEL 74
CONTACTER TOFINO TRAFFIC SUR LA VOIE VHF 74
FISHING ZONE 5
ZONE DE PÊCHE 5
WP

Figure 11-1. La Perouse stations along the west coast of Vancouver Island.

Line P is a series of oceanographic stations extending from the mouth of the Juan de Fuca Strait, south of Vancouver Island, to Ocean Station Papa (OSP; P26) at 50° N 145° W, in the Pacific Ocean (Figure 11-2). The Line P time series is one of the longest oceanographic time series in the world, with data going back to 1956. Fisheries and Oceans Canada visits Line P three times per year, usually in February, June, and August.

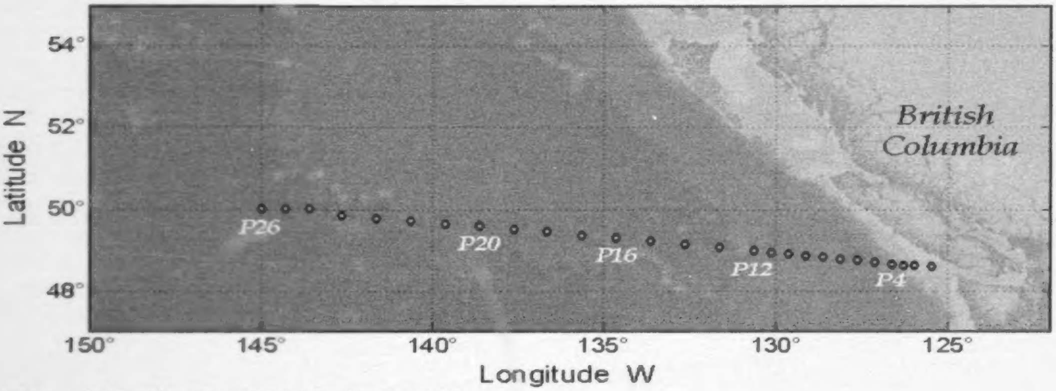

Figure 11-2. Line P and Station Papa (P26).

After following the warm water "Blob" since 2013 there is a strong curiosity regarding the presence or absence of these anomalous waters in 2015. Over the last three years, the temperature anomaly compared to the 1981-2010 average reached its peak in August 2015, as shown in Table 11-1. August seems to be the month most affected by warming in each of these years.

The temperature anomalies along Line P with respect to the 1981-2010 averages are displayed in Figure 11-3. These figures show that the maximum anomaly was situated below the surface in June and August, making it invisible to satellite imagery. This was also very clear in the May/June temperature anomalies along onshore-offshore sections on the La Perouse cruise (Figure 11-4)

Table 11-1. Temperature anomaly ranges, over all sampled depths for each cruise from February 2013 to August 2015 with respect to the 1981-2010 averages, showing the very intense anomaly in August 2015.

Cruise	Temp. anomaly minimum °C	Temp. anomaly maximum °C
February 2013	-1.89	0.38
June 2013	-2.20	2.05
August 2013	-3.54	2.99
February 2014	-2.44	2.06
June 2014	-2.30	3.57
August 2014	-1.68	4.22
February 2015	-0.45	2.88
June 2015	-1.06	3.89
August 2015	-1.70	6.13

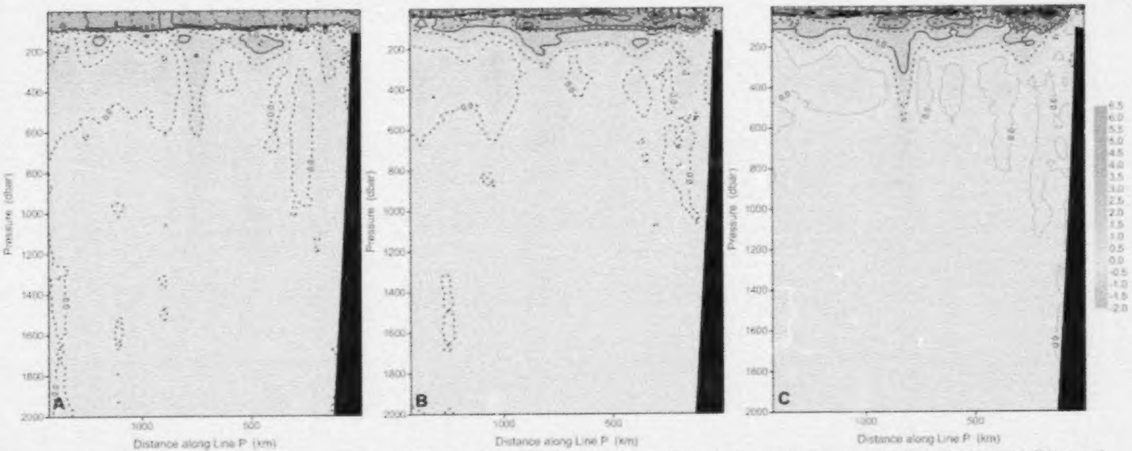

Figure 11-3. Temperature anomaly along Line P in February 2015 (panel A), June 2015 (panel B) and August 2015 (panel C) with respect to the 1981-2010 averages. All three panels are on the same scale of temperature anomaly in °C.

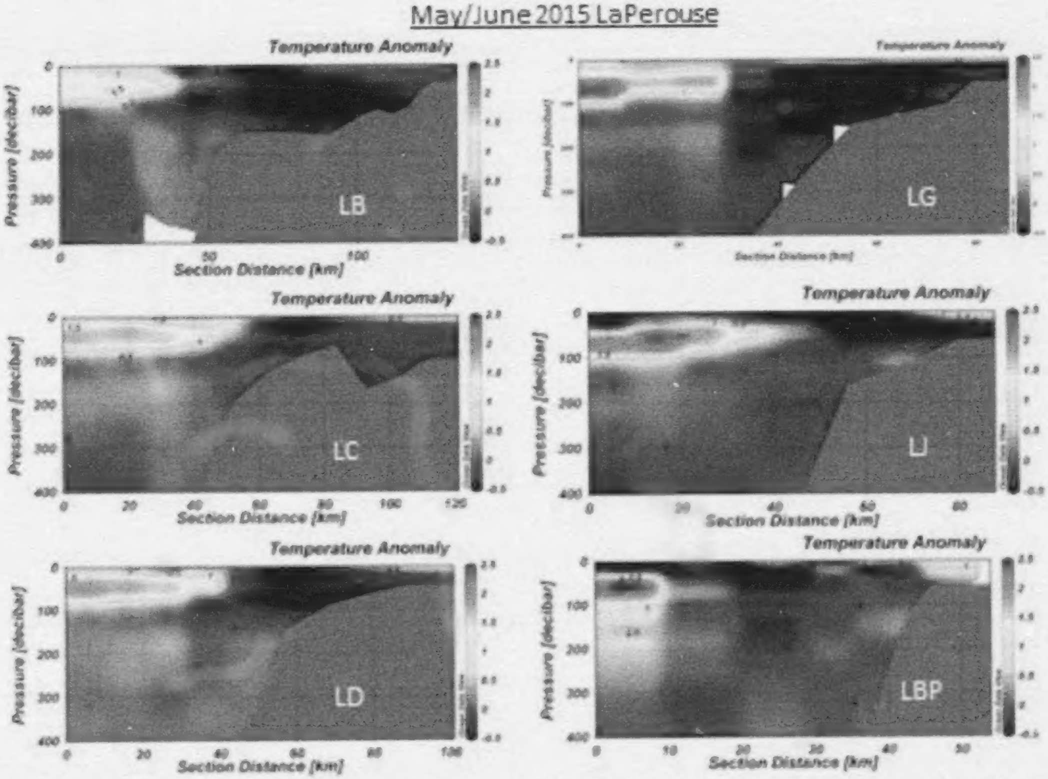

Figure 11-4. Temperature anomaly sections along La Perouse survey lines. Sections are arranged south to north, moving from upper left to lower right panels.

During the August Line P cruise we visited Station P4 – situated at 48°39 N, 126°40 W, about 87 km along the line from P1 on the continental shelf (1315 m) – on the outbound leg at the beginning of the cruise and again on the return leg. The first casts were taken on 21 August, 2015 whereas the second visit occurred 11 days later on 1 September. Figure 11-5 shows how dynamic these shelf waters can be in temperature, salinity, dissolved oxygen and fluorescence, perhaps in part (at least near-surface) due to a large storm which passed through the region on August 28. Unfortunately we could not sample the outer stations of the LD line extending from central Vancouver Island – the stations closest to P4 – during the La Perouse cruise in September so we do not know if the waters changed rapidly again following this event.

This change can also be seen in thermosalinograph data (5 m depth; Figure 11-6) where the warmer water had moved several miles onshore during those 11 days.

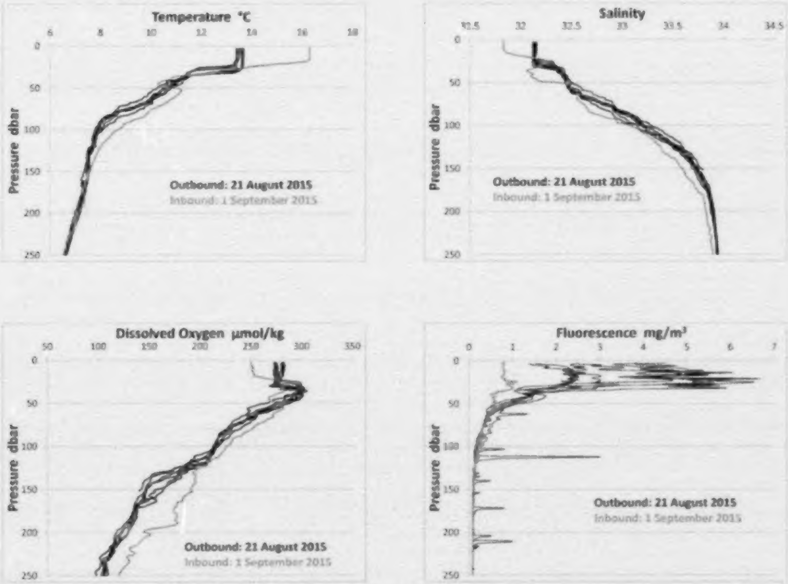

Figure 11-5. Differences in temperature, salinity, dissolved oxygen and fluorescence between the first time Station P4 was sampled on 21 August 2015 (black profiles) and when P4 was sampled again on the return leg of the cruise on 1 September 2015.

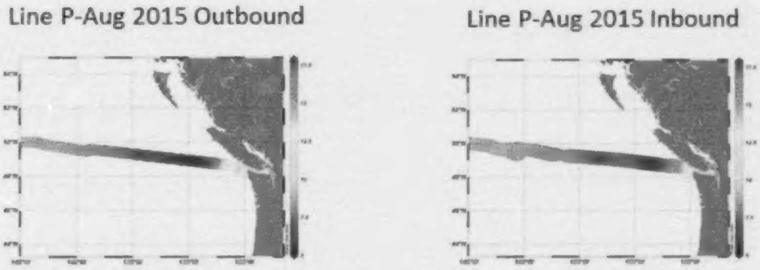

Figure 11-6. TSG temperature along track-Outbound vs. Inbound.

High temperature anomalies along La Perouse survey lines in September had reached the surface and in most cases had moved further inshore (Figure 11-7). The subsurface temperature anomaly intensified coast-wide in May, but as it moved inshore and shallowed over the summer it appeared to be disrupted by upwelling or other processes by September (Figure 11-8).

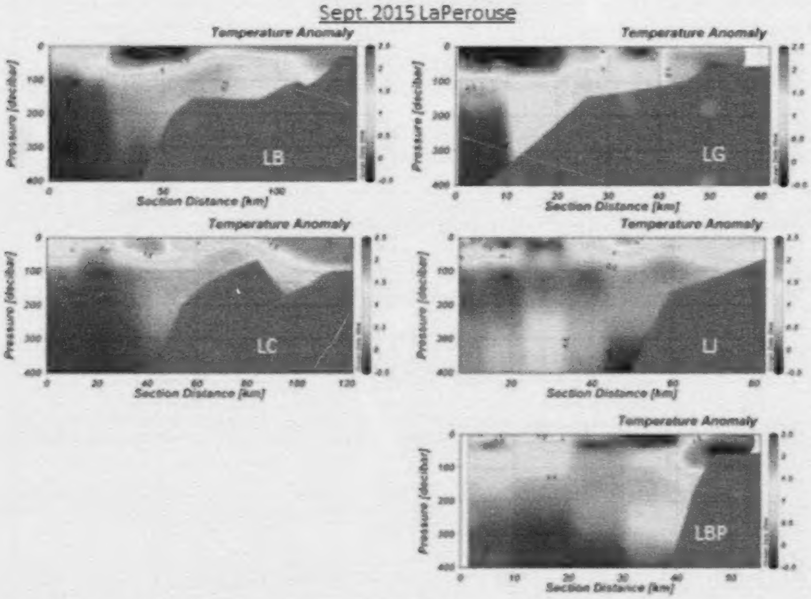

Figure 11-7. September 2015 Temperature anomalies along La Perouse survey lines.

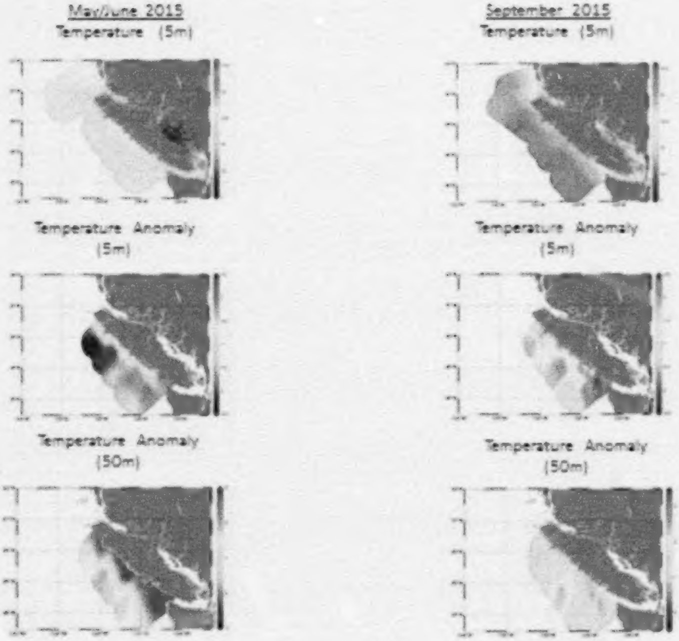
May/June 2015
Temperature (5m)
Temperature Anomaly (5m)
Temperature Anomaly (50m)
September 2015
Temperature (5m)
Temperature Anomaly (5m)
Temperature Anomaly (50m)

Figure 11-8. Temperatures (5 m depth) and anomalies (5 m and 50 m depth) along the coast in May/June and September 2015.

12. SATELLITE AND BUOY OBSERVATIONS OF B.C. WATERS

Jim Gower[1] and Stephanie King[2]

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12.1. Highlights

- Buoys show warming effects of the warm "Blob" and El Niño
- Satellites show early bloom after seeding from Desolation Sound, Jervis/Sechelt and Howe Sound, and high chlorophyll in summer on the west coast of Vancouver Island.
- Buoy and ferry data show spring bloom in the Strait of Georgia was early in 2015, starting on February 21 in the northern Strait and March 7 in the southern Strait.

12.2. Buoys show warming effect of the Blob

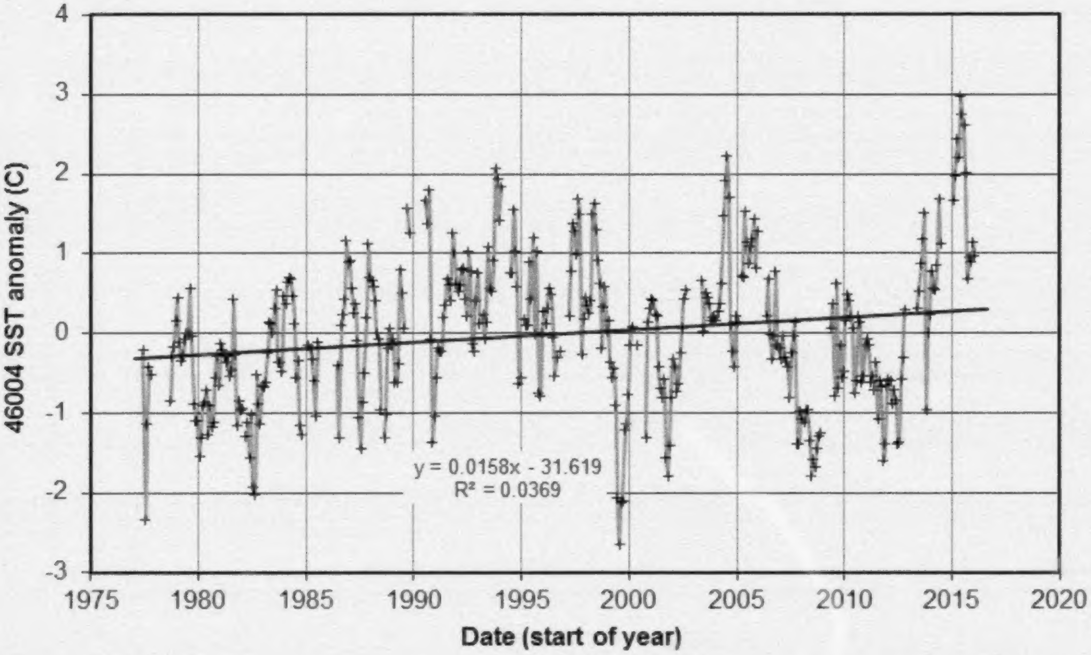

Figure 12-1. Monthly average sea surface temperatures from the offshore "Middle Nomad" weather buoy 46004 showed an all-time record warm anomaly of 3.0 °C in May of 2015, at a time when the El Niño was building on the equator.

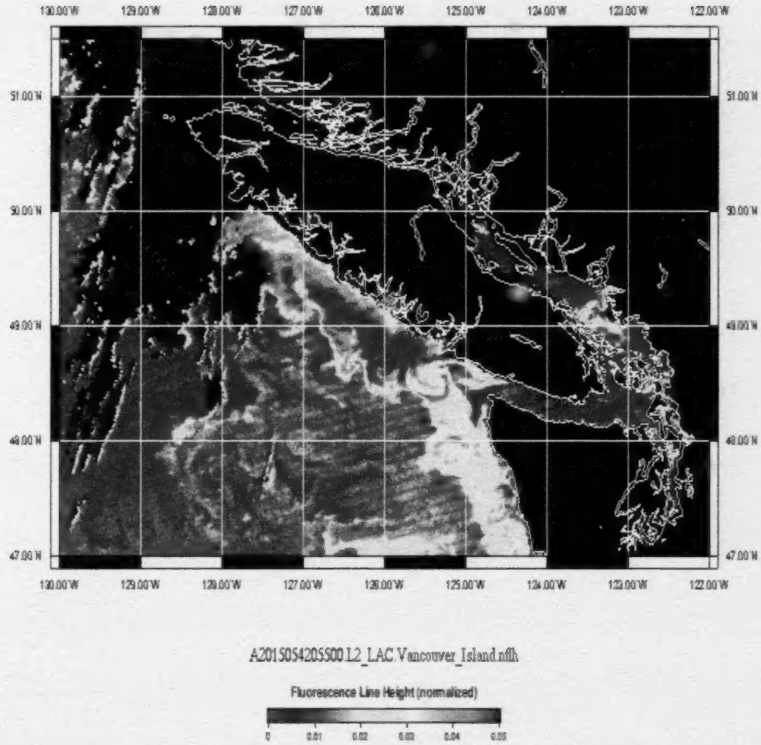
130.00'W
129.00'W
128.00'W
127.00'W
126.00'W
125.00'W
124.00'W
123.00'W
122.00'W
51.00'N
50.00'N
49.00'N
48.00'N
47.00'N
A2015054205500.L2_LAC.Vancouver_Island.nflh
Fluorescence Line Height (normalized)
0
0.01
0.02
0.03
0.04
0.05

Figure 12-2. NASA MODIS Aqua standard processing fluorescence image showing high chlorophyll in an early spring bloom off the west coast of Vancouver Island on day 54, February 23 2015, before the spring bloom in the Strait of Georgia.

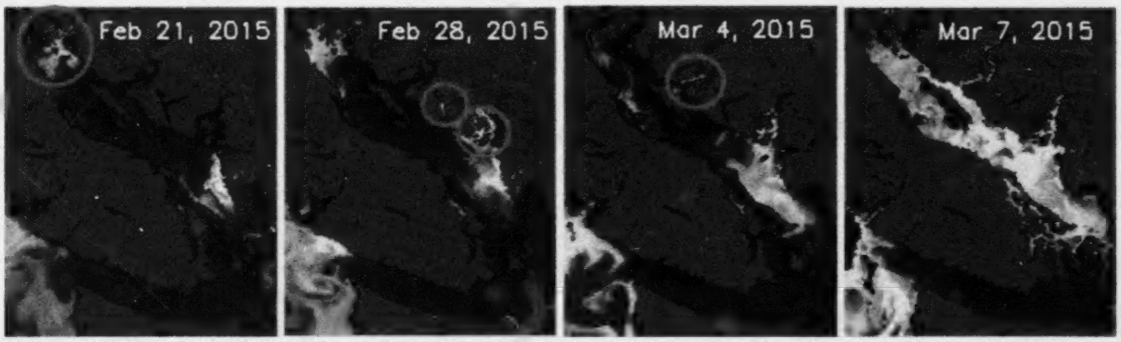
Feb 21, 2015
Feb 28, 2015
Mar 4, 2015
Mar 7, 2015

Figure 12-3. NASA MODIS Aqua fluorescence images for three days leading up to the main spring bloom (left 3 panels). Red circles indicate areas where blooms in inlets occur before high chlorophyll values are observed in adjacent areas of the Strait of Georgia. The MODIS image on March 7 (right panel) shows the bloom covering almost the entire Strait.

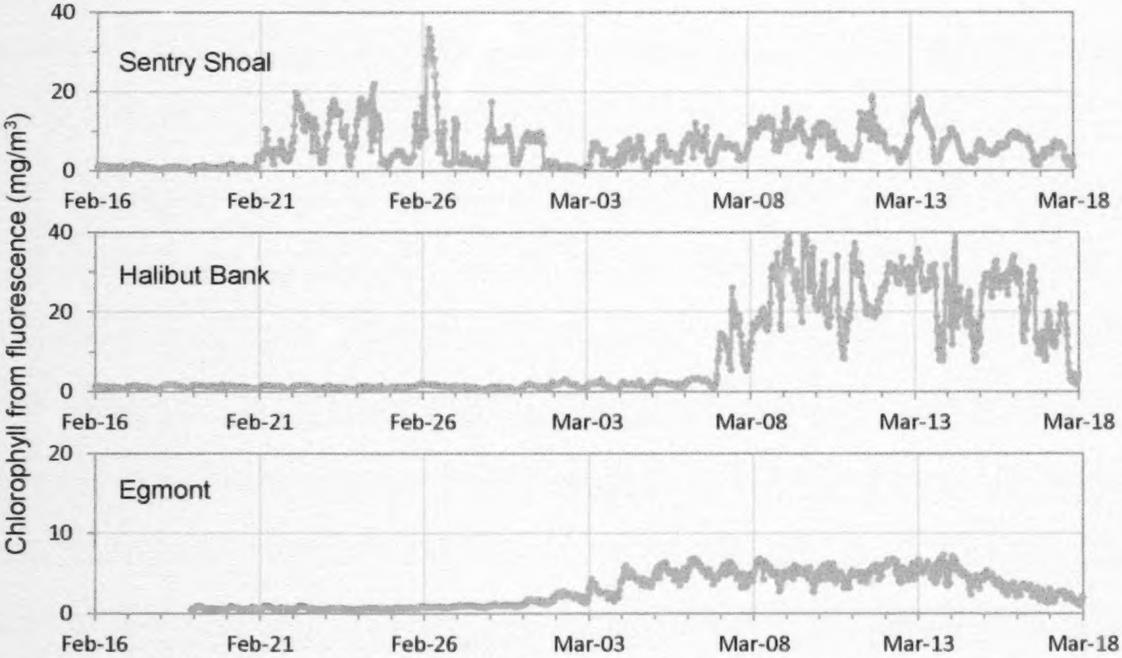

Figure 12-4. Time series from fluorometers deployed on two weather buoys in the Strait of Georgia, 46131 at Sentry Shoal in the northern Strait (top panel) and 46146 at Halibut Bank in the central Strait (middle panel) show the early bloom in the north and the later, main bloom, in the central Strait. The time series from Egmont (deployed on February 18, bottom panel) shows the bloom in Sechelt and Jervis Inlets that appears to have contributed to seeding the main bloom in the Strait, as discussed by Gower and King (2012) and Gower et al. (2013), leading to the relatively early bloom date in 2015.

12.3. Acknowledgements

Fluorometer time series data in Figure 12-4 are provided thanks to funding from the Pacific Salmon Foundation.

12.4. References

Gower, J., and King, S. 2012. Use of satellite images of chlorophyll fluorescence to monitor the spring bloom in coastal waters, Int. J. Rem. Sens., 33:23, 7469-7481 PORSEC 2010 special issue. http://dx.doi.org/10.1080/01431161.2012.685979

Gower, J., King, S., Statham, S., Fox, R., and Young, E., 2013. The Malaspina Dragon: a newly-discovered pattern of the early spring bloom in the Strait of Georgia, British Columbia, Canada, Progress in Oceanography, 115, 181-188, doi: http://dx.doi.org/10.1016/j.pocean.2013.05.024

13. PHYTOPLANKTON IN SURFACE WATERS ALONG LINE P AND OFF THE WEST COAST OF VANCOUVER ISLAND

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13.1. Highlights

- Associated with the pool of warm water, nutrient renewal from vertical transport was restricted in the winter of 2014/15 in the northeast Pacific, due to increased stratification. As a result, nitrate depletion at the surface extended farther westward in June and August 2015.
- Low chlorophyll concentrations and an increase in the abundance of cyanobacteria were observed in the upper layer of the low nitrate region of Line P in June and August 2015. Farther offshore, chlorophyll concentrations were within the range of values observed in previous years.
- On the continental shelf of the west coast of Vancouver Island, nitrate concentrations in May and September 2015 were within the range of values from previous years.
- In May 2015, diatoms dominated and phytoplankton biomass was high at the continental shelf and outer coast. In September 2015, phytoplankton biomass was low and community composition was similar to previous years.

13.2. Summary

Phytoplankton abundance and community composition are key factors influencing trophic processes and biogeochemical cycles in the ocean. Concentrations of nutrients, chlorophyll-*a* ("chl", an indicator of phytoplankton biomass) and phytoplankton pigments are measured on DFO cruises three time a year in February, June, and August/September along Line P in the northeast subarctic Pacific and twice a year in May/June and early September off the west coast of Vancouver Island. Sampling is carried out at 27 stations along Line P (Figure 13-1) and along a series of transects on the west coast of Vancouver Island, extending from the mouth of the Juan de Fuca Strait in the south to Cape Scott in the north (Figure 13-3). Phytoplankton pigments are used to estimate the abundance of phytoplankton groups

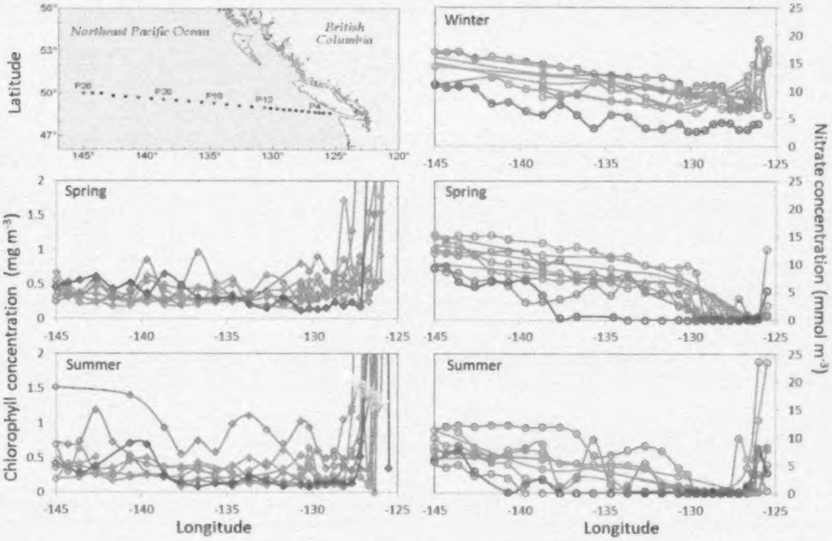

Figure 13-1. Location of sampling stations, chlorophyll-a (mg/m^3) and nitrate (mmol/m^3) in surface waters along Line P in winter, spring and summer of 2015 (red symbols) and 2008-2014 (blue symbols).

using a factor analysis algorithm (CHEMTAX) that calculates concentrations based on biomarker pigments.

Nutrient concentrations are usually high (>5 mmol m^{-3}) and chlorophyll concentrations low (<0.5 mg m^{-3}) year around in the Fe-poor prymnesiophyte-dominated offshore waters, whereas high seasonal variability in phytoplankton biomass occurs in the nutrient-rich diatom-dominated inshore waters on the continental shelf. Anomalously high surface temperature persisted into 2015 in the Gulf of Alaska. Nutrient renewal from vertical transport of nutrient-rich deeper water into the surface layer was restricted in the winter of 2014/15 due to increased stratification. As a result, nitrate depletion extended farther westward in June and August 2015 and chl concentrations were lower in the nutrient-limited region (Figure 13-1). Offshore, chlorophyll concentrations were within the range of values observed in previous years.

Phytoplankton assemblage composition shows the dominance of diatoms inshore, and a significant increase in the relative abundance of cyanobacteria in the nutrient-limited region in June and August of 2015 compared to previous years (Figure 13-2). Offshore, there was an increase in the abundance of chlorophytes in June and of haptophytes in August of 2015.

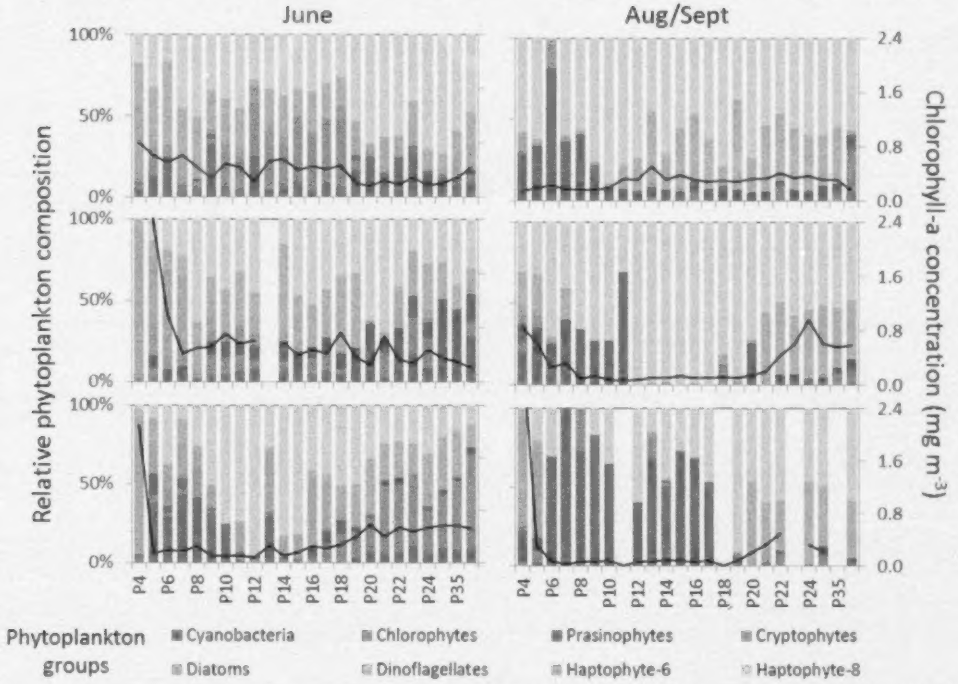

Figure 13-2 . Relative phytoplankton composition and chl concentration (black lines) in the surface layer at stations along Line P (see Figure 13-1) in June and August/September of 2013 (top panels), 2014 (middle panels), and 2015 (lower panels).

Nutrient and chl concentrations are highly variable in surface waters off the west coast of Vancouver Island. On the continental shelf, nutrient concentrations are usually lower in May compared to September. In general, chl is usually high (> 5 mg/m^3) on the continental shelf off southern Vancouver Island where blooms of phytoplankton (>20 mg/m^3 chl) are often observed in May and/or September. At stations beyond the continental shelf, chl and nutrient concentrations are usually lower than on the continental shelf. In 2015, nutrient concentrations

(Figure 13-3) were within the range of values observed in previous years. High chl concentrations (>10 mg/m^3) were observed in May of 2015 near shore and off Brooks Peninsula (Figure 13-3). By September, chl concentrations were at the lower range (<5 mg/m^3) of previous observed values.

On average, diatoms dominate phytoplankton biomass at the ocean surface along the continental shelf although dinoflagellates are found to occasionally dominate in September (Figure 13-4). At stations beyond the continental shelf (outer coast), phytoplankton community composition is more diverse and variable than on the continental shelf with dinoflagellates, diatoms, haptophytes and cryptophytes dominating at times and far fewer diatoms than seen on the coast.

In May 2015, and similar to previous years, diatoms dominated the phytoplankton biomass on the continental shelf, except at Line CS where several phytoplankton groups were present in similar abundance. In contrast to previous years, diatoms also dominated at most locations in the outer coast, whereas a mixed population was observed in previous years. In September 2015, phytoplankton biomass was lower than in previous years on the continental shelf but the phytoplankton community composition was similar to previous years. Chl was also lower on the outer shelf where a diverse phytoplankton community composition was found similar to those observed in previous years.

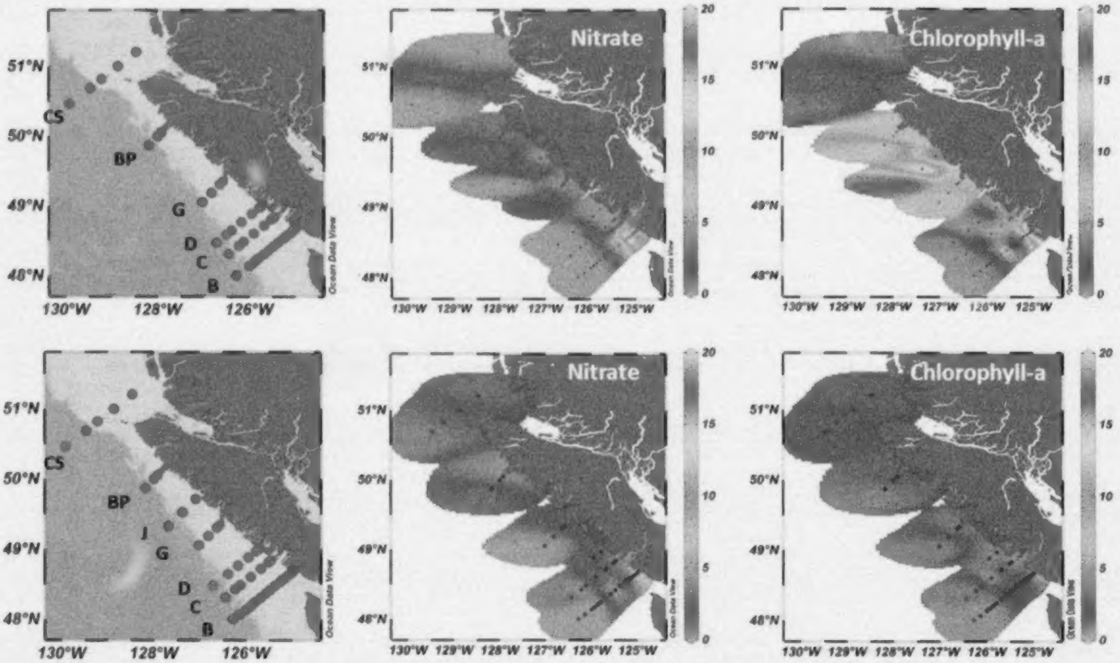

Figure 13-3. Location of sampling stations, nitrate (mmol/m^3) and chlorophyll-a (mg/m^3) at 5 m depth over the study area in May (top row) and September (bottom row) of 2015.

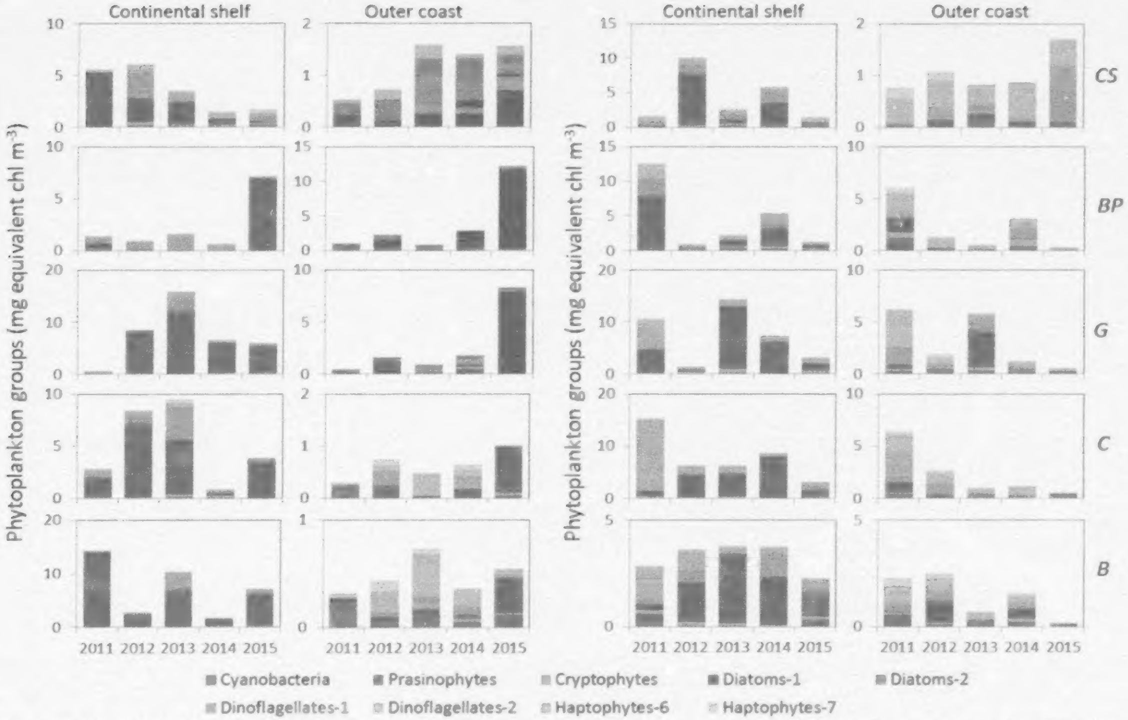

Figure 13-4. Time-series of mean phytoplankton composition at the surface at stations on the continental shelf and outer coast for Line B, C, G, BP and CS (Figure 13-3) in May (left panels) and September (right panels).

Along the North American coast, exceptional phytoplankton blooms were observed by satellite data from May to August 2015. They were unusual in terms of their spatial extent (California to Alaska), duration (May to Aug) as well as for the presence of phytoplankton species that produce a toxin, domoic acid (Trainer et al., 2015). In early July 2015 at the shelf break off Vancouver Island, *Pseudo-nitzschia fraudulenta* (a potential domoic acid producer) comprised 32% of all diatoms, and 19% of all microplankton sampled (I. Perry, DFO, personal communication). DFO does not have a harmful algal bloom monitoring program in the Pacific region but the Canadian Food Inspection Agency (CFIA) routinely tests shellfish for domoic acid levels, along with other toxics. In early July 2015, routine monitoring of shellfish in coastal harvesting areas by the CFIA detected toxin levels above the Canadian Shellfish Sanitation Program's safe allowable standards in three areas along northwest Vancouver Island. These areas were closed to shellfish harvesting by DFO. Toxin levels in the United States were much higher than in British Columbia, possibly due to differences in ocean conditions.

13.3. References

Trainer, V.L., McCabe, R. Hickey, B. and Kudela, R. 2015. The impacts of a massive harmful algal bloom along the US west coast in 2015. PICES 2015 Annual Meeting, Book of Abstracts, p. 130.

14. LOWER TROPHIC LEVELS IN THE NORTHEAST PACIFIC

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soba@sahfos.ac.uk

14.1. Highlights

- Diatoms (the larger cells that are caught by the CPR) were very low in 2015 and there was an unusual bias towards pennate-type long, thin cells. This is consistent with reduced mixing and low nutrients (which favour cells with a high surface area to volume ratio) reported along Line P.
- Zooplankton abundance and estimated biomass were lower than average in 2015, but not exceptional. Broad community composition was not unusual.
- Jellyfish have shown an increase in prevalence in CPR samples in recent years, with a peak of more than 50% of samples in 2015.

14.2. Sampling

Sampling from commercial ships towing a Continuous Plankton Recorder (CPR) occurs approximately monthly 6-9 times per year between March and October in the off-shore NE Pacific (Figure 14-1). Each CPR sample contains the near-surface (about 7 m depth) plankton from an 18.5 km section of the transect, filtered using 270 µm mesh, and afterwards analysed microscopically to give taxonomically resolved abundance data. Data to June 2015 have been finalised at the time of writing, while samples for July to October 2015 are still only partially analysed. Several indices are now routinely updated and are summarized here.

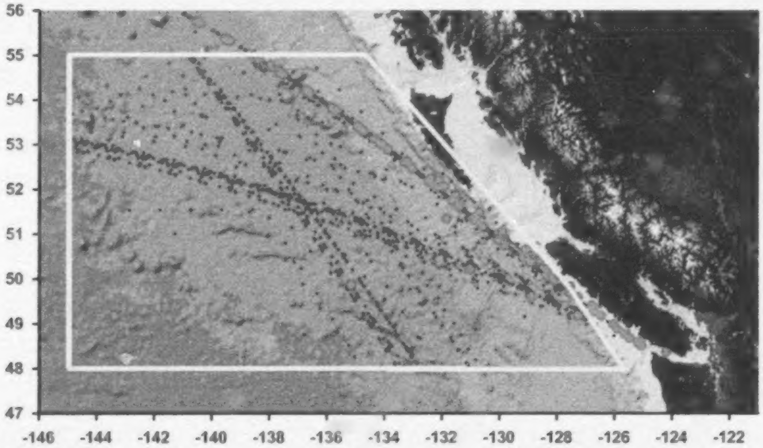

Figure 14-1. Map showing the location of the historical (dark red dots, 2000-2014) samples and those collected in 2015 (bright red points) that are used in this report (additional 2015 samples are being processed). Data are averaged for the region outlined in yellow.

14.3. Plankton indices

14.3.1. Diatoms

The CPR retains larger, especially chain forming, diatoms and an annual index of abundance is calculated. Between 2000 and 2013 there was a highly significant relationship between the mean annual Pacific Decadal Oscillation (PDO) index and the annual diatom anomaly (r^2=0.47, p<0.005). However, in 2014 and in 2015 too, diatoms were very low in numbers (Figure 14-3), not what would be expected from the strongly positive PDO at this time. Furthermore, when the composition of the diatoms was examined it was noted that the cell types that were long and thin in shape (e.g. *Proboscia* spp., *Pseudonitzschia* spp.,) were relatively more numerous in the spring of 2014 and 2015 while the rounder cell types (e.g *Thalassiosira* spp.) were much less abundant. Figure 14-2 shows that in spring 2015, for the first time, the long thin cell types made up more than 50% of the diatom community sampled by the CPR. Diatoms that are long and thin have a higher surface area: volume, meaning they are more efficient at absorbing nutrients. Their growth would therefore be favoured over the growth of round cells in low nutrient conditions, which were found along Line P in the winter/spring of 2014/2015 (Peña and Nemcek 2016).

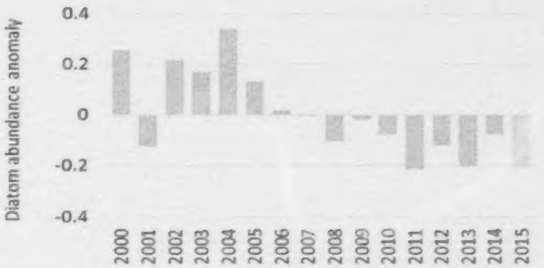

Figure 14-3. Annual abundance anomalies of large diatoms for the region shown in Figure 1. Value for 2015 is provisional.

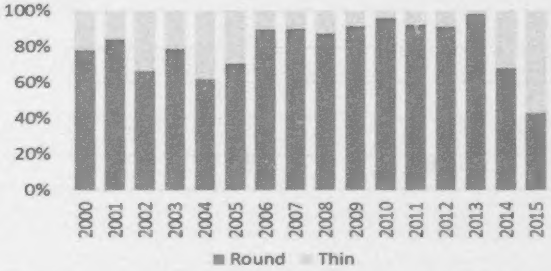

Figure 14-2. The proportion of the spring (Mar-June) diatom community comprised of either long, thin diatoms or round chain forming cells.

14.3.2. Zooplankton Abundance

The mean annual abundance of mesozooplankton was below average for 2015 (Figure 14-4) and the estimated biomass was also lower than average, though neither values were exceptional. Broad community composition showed no unusual changes in 2015, although by summer the numbers of large copepods were very low. This would be expected in a warm year when their seasonal cycle would be shifted earlier.

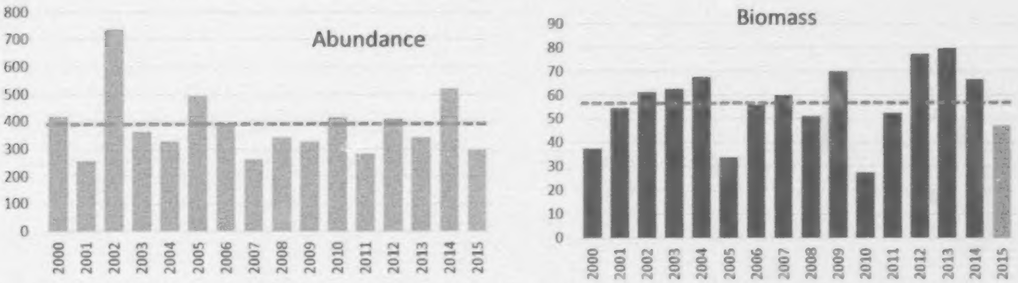

Figure 14-4. The mean annual abundance of zooplankton per sample (left) and biomass (dry weight, mg per sample) estimated using taxon-specific values (right), for the region shown in Figure 14-1. 2015 values are provisional. Red dashed lines indicate the long-term mean in each case.

14.3.3. Jellyfish occurrence.

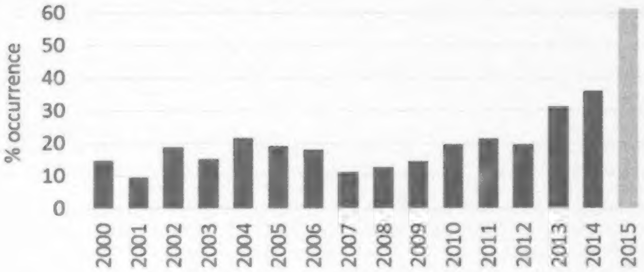

Figure 14-5. The proportion of the CPR samples that contained jellyfish material per year, for the region shown in Figure 14-1. The value for 2015 is provisional.

While jellyfish cannot be counted in CPR samples their presence is noted when nematocysts (stinging cells) are seen during taxonomic processing. The proportion of samples where jellyfish have been recorded as present has increased in recent years (Figure 14-5) and reached a maximum in 2015. Although data from the second part of 2015 are still to be completed it appears that more than 50% of samples will have had jellyfish present for the first time in the time series. Assuming that there is a positive relationship between presence in the samples and abundance in the ocean then it can be concluded that jellyfish were more abundant in the region in 2015 than in any other year.

14.4. Summary

The CPR data show some effects of the anomalously warm conditions (Bond et al. 2015) on lower trophic levels in 2015; reduced diatoms and a shift in their community composition, lower zooplankton abundance and an increase in jellyfish. These changes are likely to have an impact on the functioning of the oceanic food web.

See http://pices.int/projects/tcprsotnp/default.aspx for data, updates and more information.

14.5. References

Bond, N. A., Cronin, M. F., Freeland, H. and Mantua, N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophys. Res. Lett., 42: 3414–3420. doi: 10.1002/2015GL063306.

Peña, A. and Nemcek, N. 2016. Phytoplankton in surface waters along Line P and off the west coast of Vancouver Island. In: Chandler, P.C., King, S.A., and Perry, R.I. (Eds.). State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2015. Can. Tech. Rep. Fish. Aquat. Sci. 3179: viii + 230 p. (this volume).

15. ZOOPLANKTON ALONG THE B.C. CONTINENTAL MARGIN, 2015

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15.1. Highlights

- Consecutive years of warm water intrusions from a southerly direction are effectively making the west coast of Vancouver Island like the nearshore California Current: high in gelatinous taxa and low in crustaceans.
- In 2015 Sub-Arctic and boreal copepods continued to decline as southern copepod species increased.
- Massive increases in gelatinous animals off the west coast, led by the incredible abundance of doliolids, coupled with the large phytoplankton bloom that persisted from early spring well into the fall made 2015 a very different year.
- *Limacina helicina* continued to decline along the west coast of Vancouver Island.

15.2. Summary

Zooplankton time-series coverage of the British Columbia continental margin extends from 1979 to present for southern Vancouver Island (SVI), from 1990 to present for northern Vancouver Island (NVI; although with much lower sampling density and taxonomic resolution in 1991 to 1995), and from 1998 to present for southern Hecate Strait (with some scattered earlier sampling between 1983 and 1997). For this report the figures will cover 1990 to 2015. The 'standard' sampling locations in SVI, NVI and Hecate regions are shown in Figure 15-1. Additional locations are included in averages when they are available. Samples are collected during DFO research surveys using vertical net hauls with black bongo nets (0.25 m^2 mouth area, 0.23 mm mesh aperture), from near-bottom to sea surface on the continental shelf and upper slope, and from 250 m to surface at deeper locations. We have also recently compiled historic data from various shorter term sampling programs in the Strait of Georgia (SoG). Most of the SoG sampling did not follow a standard grid or sampling protocols. Because of time varying taxonomic resolution, the SoG data were merged into broader categories (size classes within major taxa). Our analyses-to-date of the SoG time series are described in Mackas et al. (2013a and 2013b).

We routinely estimate abundance and biomass for more than 50 zooplankton species in the SVI, NVI, shelf and offshore. For these regions, seasonal variability is intense and somewhat repeatable from year-to-year. However, because sampling dates vary from year to year, simple annual averages of observations confound seasonal with interannual differences. We deal with this by first estimating a multi-year average seasonal cycle (i.e. "climatology") for each region, using the data from the start of each time series through 2008, and then using these climatologies as baselines against which we can then compare monthly conditions during any single year. To describe interannual variability, our approach has been to calculate within each year a regional, logarithmic scale biomass anomaly for each species and for each month that was sampled in a given year. We then average the monthly anomalies in each year to give an annual anomaly (see Mackas 1992 & Mackas et al. 2001 for mathematical details; for SoG see Mackas et al. 2013a). It is important to note that the anomalies are log scale and therefore multiplicative on a linear scale: an anomaly of +1 for a given taxon means that taxon had 10X higher biomass than in the climatology; an anomaly of -1 means the biomass was 1/10th the climatology.

We have learned from our own and from other west coast time series (Mackas et al. 2006), that zooplankton species with similar zoogeographic ranges and ecological niches usually have very similar anomaly time series. We therefore summarize the interannual variability of multiple species by averaging within species groups. For example, the group 'boreal shelf copepods' is a composite of the copepods *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis;* all of which have distribution ranges that extend from southern Oregon to the Bering Sea. The group 'subarctic oceanic copepods' is a composite of *Neocalanus plumchrus*, *N. cristatus*, *N. flemingeri* and *Eucalanus bungii*; all of which inhabit deeper areas of the subarctic Pacific and Bering Sea from North America to Asia. A third group, 'southern copepods' is a composite of species from the five genera *Clausocalanus, Calocalanus, Ctenocalanus, Mesocalanus* and *Paracalanus* with ranges centered about 1000 kilometers south of our study areas (either in the California Current and/or further offshore in the North Pacific Central Gyre). Southern chaetognaths (CHAETsouth) are a mix of *Mesosagitta minima* and *Parasagitta euneritica*, both have distributions centered off California/Mexico. Northern chaetognaths (CHAETnorth) is represented by *Parasagitta elegans*

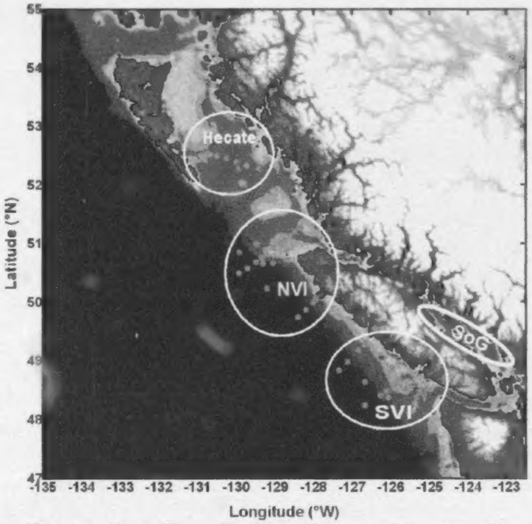

Figure 15-1. Zooplankton time series sampling locations (red dots) in B.C. marine waters. Data are averaged within major statistical areas indicated by ovals; the SVI and NVI regions are further classified into shelf and offshore subregions. The PNCIMA (Pacific North Coast Integrated Management Area) includes both NVI and Hecate stat areas. Preliminary results from the SoG time series are described in Mackas et al. 2013a.

Figure 15-2 shows anomaly time series for these copepod species groups and representative chaetognaths and euphausiids in WCVI statistical areas. The range of interannual biomass variability within a species or species group is about one log unit (i.e. factor of 10). This is 2-3 times greater than the interannual variability of total biomass in our regions. Other features to note are that anomalies often persist for several years and that, in addition to the covariation within species groups mentioned above, there is strong covariation between some species groups. The clearest and most gradually varying signals have been in the three copepod groups and in the chaetognaths. Cool years such as the early 1980s, 1999-2002, and 2007-9 had positive anomalies of boreal shelf and subarctic copepods, and northern chaetognaths. Warm intervals such as 1983, 1993-1998, 2004-2005 and 2010 tended to have negative anomalies of these taxa, but positive anomalies of southern copepods and southern chaetognaths. From previous work, we know that positive anomalies of the cool water zooplankton community off Vancouver Island are also associated with good local survival and growth of juvenile salmon, sablefish, and planktivorous seabirds (Mackas et al. 2007; M. Trudel, DFO, personal communication). Be aware that the y axis changes with each taxa group.

2015 started off as a warm year in both the near shore and offshore regions, with strongly positive anomalies for southern zooplankton; especially doliolids. This increased throughout the year as warm offshore water with higher abundances of southern oceanic zooplankton species moved towards the coast. By October the whole continental margin of B.C. was inundated with large masses of gelatinous animals as the El Niño got into full swing. Early in the year, warm water moved from offshore oceanic waters on to the shelf. By September the south to north alongshore movement of water and zooplankton reflected this with more southern coastal species along the shelf mixing with southern oceanic species.

There was no moderation of the annual anomaly signal in all taxa groups this year (present in the last two years) that is normally seen as seasons move from cold winter into warm fall. Since there was relatively no cold winter, what was positive at the beginning of the year stayed as a positive signal. This is a similar situation to 2005, with no winter cooling. 2015 started with warm water parked in the offshore area which was then pushed onto the shelf by storms. The influence of the summer intrusion onto the shelf of warm water was strongest in SVI but by the late summer the more northerly NVI and Hecate areas were inundated with southern fauna.

Both SVI and NVI nearshore and shelf regions had a similar seasonal trend toward more southern copepods which was stronger than in 2014 (Figure 15-2). Boreal shelf copepods fared better in the offshore regions in NVI and in Hecate with a slight positive trend, however, the overall trend in these areas was negative for boreal and sub-Arctic species. As more September/October samples are analyzed, it is expected this will enhance the warm water signal within the anomalies. One of the main reasons for less boreal copepods is the near absence of *Pseudocalanus* species on the shelf in the south and the replacement of *Calanus marshallae* with *Calanus pacificus* in the north. The influx of southern species brought in some rare animals, not usually seen off WCVI except in large El Niño events: *Mecynocera clausi, Acartia tonsa, Pleuromamma gracilis, Pleuromamma indica, Paracalanus quasimodo, Parvocalanus crassirostris, Oithona tenuis, Rhincalanus nasutus*; to name a few.

Boreal copepods were reduced along the shelf in both the north and south coast, whereas in the Hecate region it was the sub-arctic copepods that dropped in biomass as the southern copepods moved into the area. This indicates shelf water moving northerly, not from the west as was seen in 2014. Southern copepods are positive in all regions for the second year in a row (Figure 15-2 and Figure 15-3). Subarctic oceanic copepods are typically found along the shelf break in the spring so the expectation was that they should do better in the offshore environment than on the shelf. For all regions, both on the shelf and offshore areas, the annual anomalies of the subarctic oceanic copepods were negative in 2015 (Figure 15-2).

Euphausiids continue to trend positive over the last five years in both WCVI and Hecate regions. Off California, both *Euphausia pacifica* and *Thysanoessa spinifera* are the dominant species suggesting that warmer waters may enhance their reproductive success though, in the past, warming events tended to favour *E. pacifica* over *T. spinifera*. *Thysanoessa gregaria* and *Nyctiphanes simplex*, whose distribution is centred from California and south, were found in small numbers along the shelf in September. *Euphausia recurva*, a subtropical central Pacific species was identified from a few February 2016 samples.

A major taxa group of, not discussed here as part of the anomalies series, is the Hyperiids. They are difficult to quantify directly because their life cycle involves commensal to parasitic interaction with Cnidaria and Urochordates. Within this group, the changes have been: *Primno abyssalis* giving way to *Primno brevidens*; *Vibilia propinqua* being replaced by *Vibilia cultripes* and *V. armata*; plus the reduction in number of the usually common *Themisto pacifica* but an increase in rare species such as *Oxycephalus clausi*, *Dairella californica* and *Streetsia challengeri*.

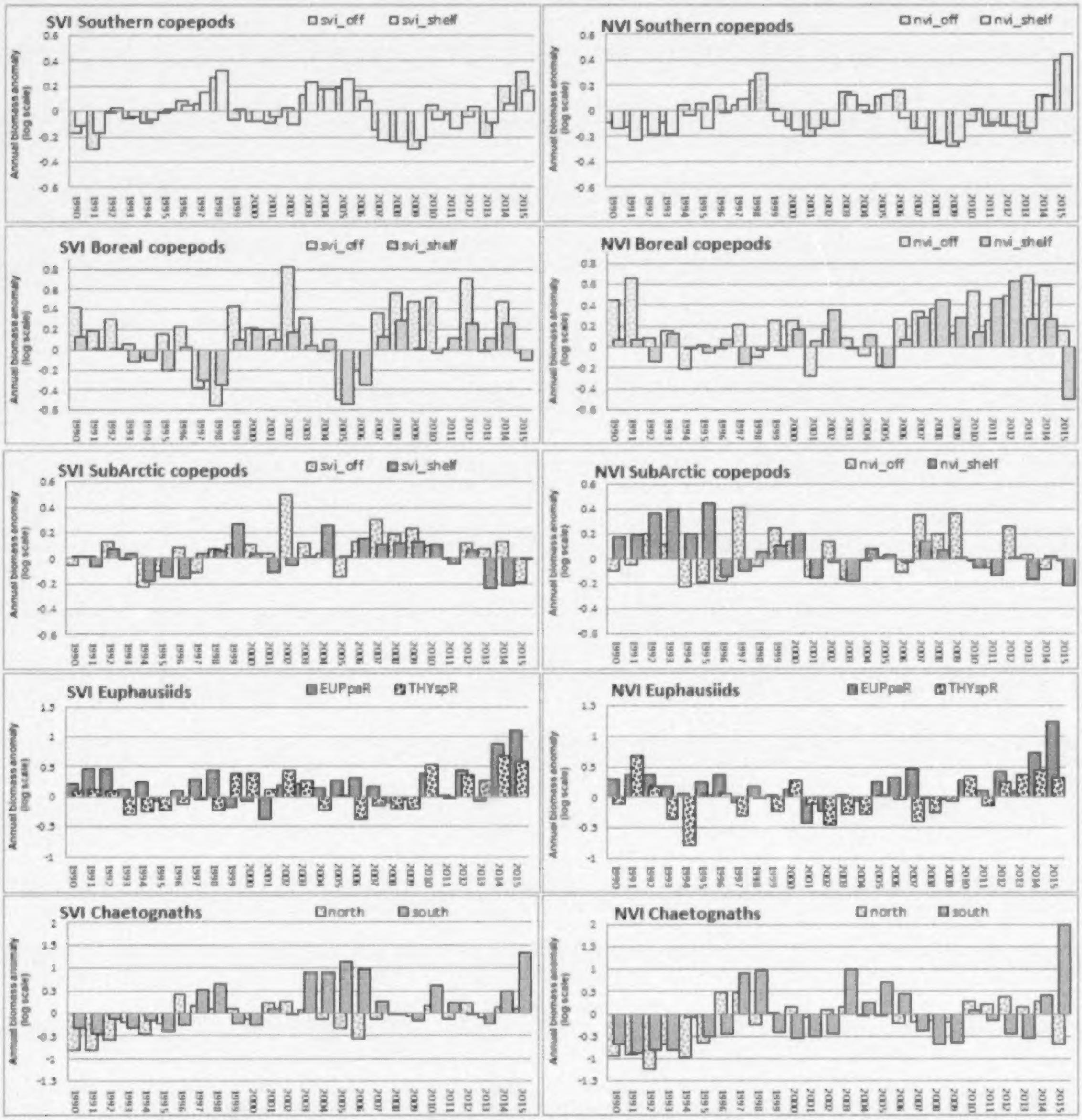

Figure 15-2. Zooplankton species-group anomaly time series (vs climatological baseline) for the SVI (left) and NVI (right) regions shown in Figure 15-1. Bar graphs are annual log scale anomalies. Cool years favor endemic 'northern' taxa; warm years favor colonization by 'southern' taxa. See earlier State of the Ocean reports for pre1990 anomalies. R in Euphausiids represents: corrected for day/night tows. EUPpa: Euphausia pacifica; THYsp: Thysanoessa spinifera; CHAET; Chaetognaths divided into north/south species group

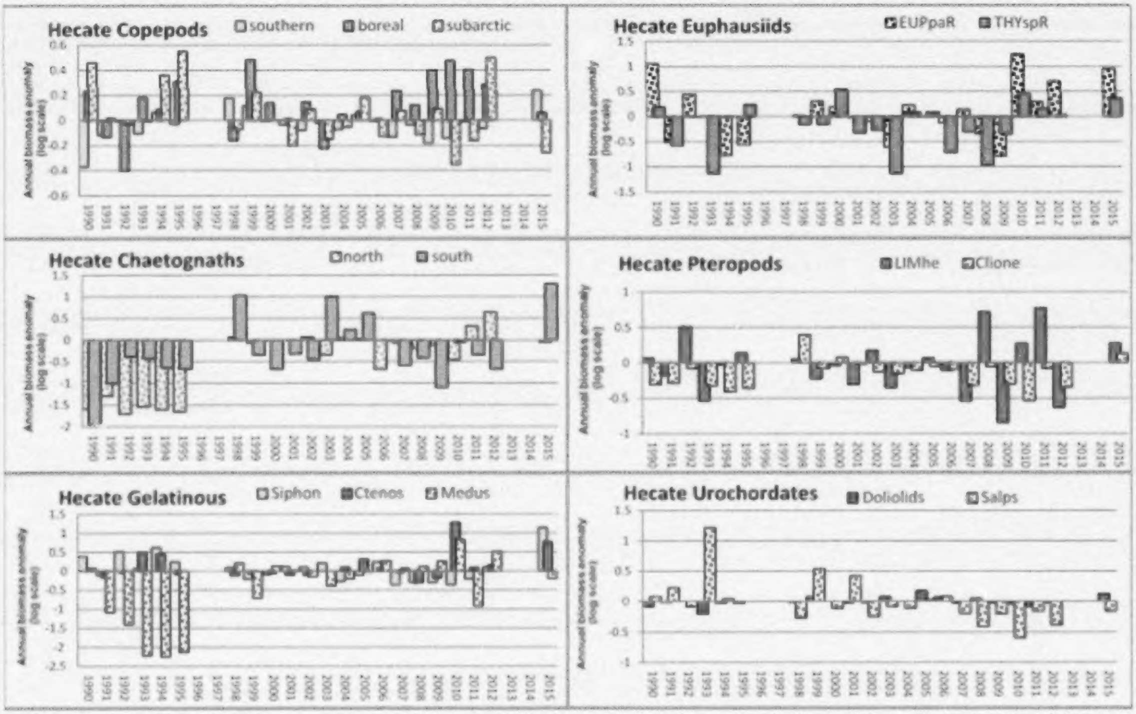

Figure 15-3. Zooplankton species-group anomaly time series (vs climatological baseline) for the Hecate Strait region shown in Figure 15-1. Bar graphs are annual log scale anomalies. Cool years favor endemic 'northern' taxa; warm years favor colonization by 'southern' taxa. See earlier State of the Ocean reports for pre1990 anomalies. R in Euphausiids represents: corrected for day/night tows. EUPpa: Euphausia pacifica; THYsp: Thysanoessa spinifera; CHAET; Chaetognaths divided into north/south species groups. Blank years mean no samples: 1996-97; 2013-14.

Several high-order zooplankton taxa (with widely differing ecological niches) are classified as "gelatinous zooplankton". However, all have high to very high peak reproductive rates compared to the crustaceans and chaetognaths, and all tend to have "boom and bust" population time series. The most important gelatinous zooplankton groups in the SVI and NVI regions are:

- Salps and doliolids. These are planktonic tunicates, and are primarily herbivorous (broad spectrum filter feeders)
- Thecosomatous pteropods (e.g. *Limacina helicina*). These are planktonic snails. Unlike the previous two groups, their bodies are not gelatinous, but they use a large external gelatinous feeding web to capture their food.
- Hydromedusae and siphonophores ("jellyfish") and ctenophores ("comb jellies"). These are predatory on other zooplankton, sometimes on larval fishes but mainly competitors with larval fish.

Doliolids were absent or rare in nearly all years before 2003, but since then have been present in years of warm water incursions in the SVI region (and nearly as abundant in the NVI region). Years with positive doliolid anomalies have occurred throughout the time series, with 2015 being the highest recorded for doliolids (Figure 15-3). Doliolids were also abundant in Hecate Strait, from late August to October, but in lower numbers than off WCVI (Figure 15-4).

For the past three years, ctenophores have seen a positive trend in both NVI and SVI which has been consistent over the shelf and offshore areas. The main ctenophore collected is *Pleurobrachia bachei* but there has been some Horminophora, a southern species, in the offshore areas. Both the siphonophores and hydromedusae were positive for 2014, especially on the shelf and shelf break areas of Vancouver Island. For the last three years, a warm water pteropod, *Corolla spectabilis* was found on the shelf and offshore areas of all regions; last known occurrence was in 2005/2006 and 1997/1998. As with the long term trend in the copepod species groups, the net effect has been to make the zooplankton community off B.C. more like the community found in nearshore parts of the California Current System to the south of B.C., less like the historical SVI and NVI climatology, and less like the present-day zooplankton community off northern British Columbia and Alaska.

Other interesting southern zooplankton found in 2015 samples were:

- salps: *Ihlea punctata*, *Thalia democratia*, *Thetys vagina*
- pteropods: *Limacina inflata*, *Clio recurva*, *Cliopsis krohnii*
- ctenophores: *Thalassocalyce inconstans*, *Beroe forskalii*, *Beroe gracilis*
- larvaceans: *Oikopleura longicauda*, *Megalocercus*
- hydromedusae: *Cunina*, *Liriope tetraphylla*

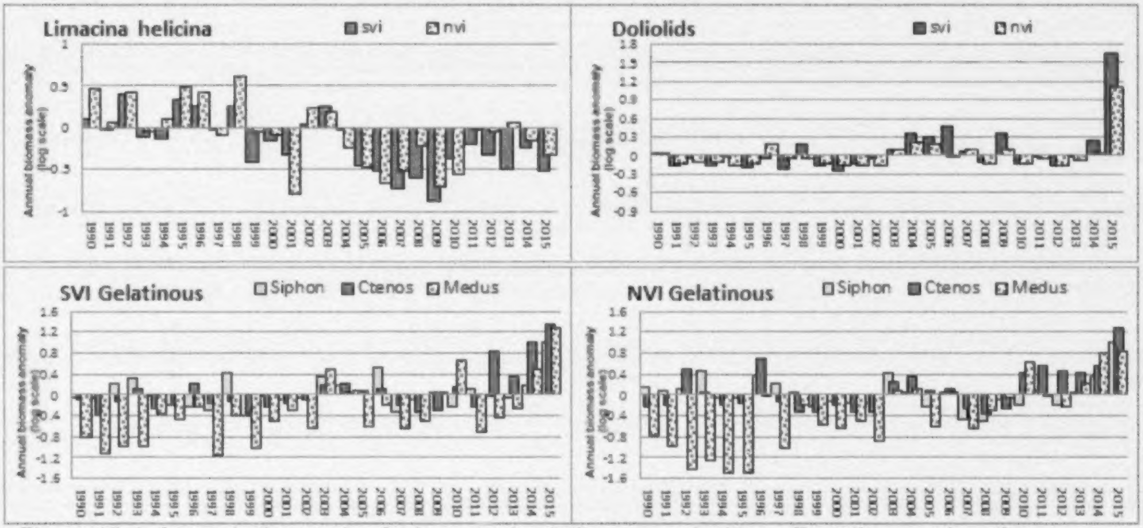

Figure 15-4. Anomaly time series for important gelatinous zooplankton off southern and northern Vancouver Island. Top panel shows Limacina helicina and doliolids (genus Dolioletta). Bottom panel hydromedusa, ctenophores and siphonophores.

WCVI had very strong anomalies for all gelatinous taxa, and Hecate Strait followed the same trend except for a weak negative trend in the hydromedusae (Figure 15-3 and Figure 15-4). *Aglantha digitale* is one of the most abundant hydromedusae in the North Pacific but it was not what was driving the positive signal in the hydromedusae off the west coast of Vancouver Island. The majority of the biomass of medusae can be attributed to the increase in numbers of *Mitrocoma, Clytia* and *Halitholus*. By late summer and into the fall, *A. digitale* was replaced by its southern counterpart *Aglaura hemistoma* whose normal distribution in the Pacific centres from 40°N to 40°S.

With the interest in ocean acidification we have included anomaly trends for *Limacina helicina*, a pelagic thecosomate (shelled) pteropod with a calcareous shell susceptible to dissolution damage if water in the top 100 m is under saturated for aragonite. The overall trend for *L. helicina* is negative; the small positive anomaly in 2013 in NVI was a result of sampling in cool spring conditions along the shelf and shelf break, but this was not repeated in 2014 or 2015. Both the shelf and offshore areas of NVI and SVI were negative for 2014 and more negative for 2015 (Figure 15-4). Limacina in Hecate Strait shows a slight positive in 2015 but without the previous years it is difficult to determine if this is a positive trend or maintaining average abundance (Figure 15-3). In an attempt to summarize and simplify, all the material presented has been condensed into two categories for the WCVI (Figure 15-5). Low and/or sporadic sampling effort in Hecate Strait makes it difficult to synopsize but the pattern are similar for the most part with NVI. Essentially, the categories are as described below *(ignoring mero- and ichthyoplankton)*:

- Crunchies: all zooplankton having a hard, chitinous exoskeleton; mainly crustaceans with high protein and lipid material – copepods, euphausiids, amphipods, decapods, etc.
- Squishies: all zooplankton with a hydrostatic skeleton; mainly gelatinous animals with high water content and low nutritional value – hydromedusae, salps, doliolids, ctenophores, etc.

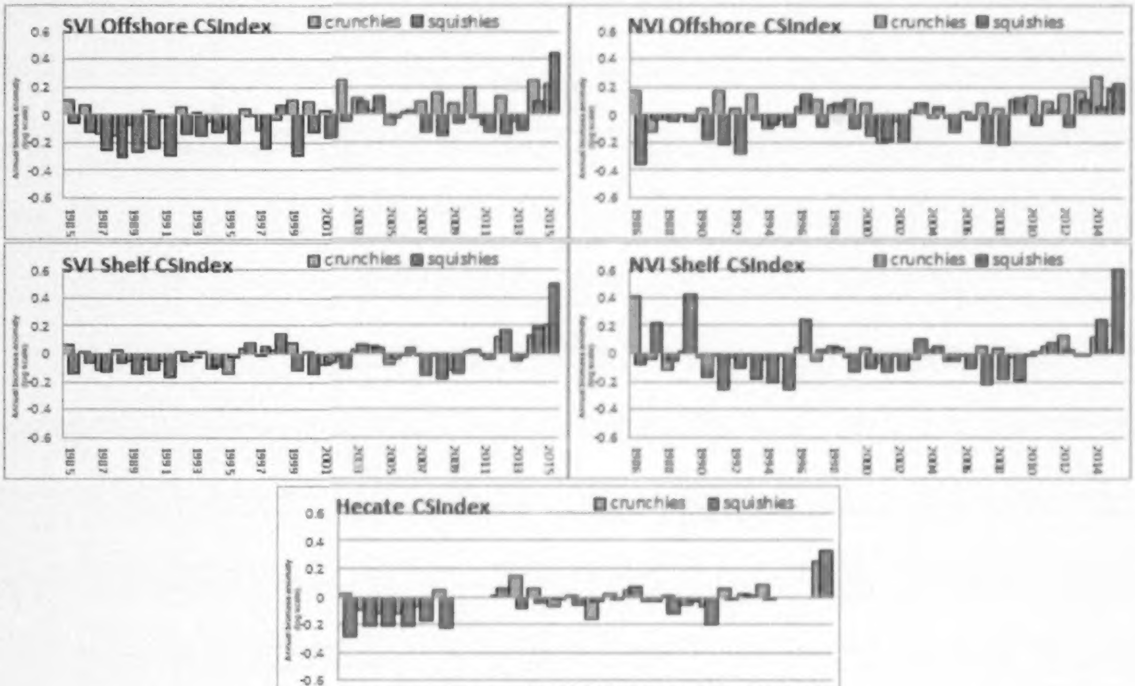

Figure 15-5. Anomaly time series for important gelatinous zooplankton ("squishies") versus important arthropod taxa ("crunchies") (ignoring mero- and ichthyoplankton) off southern and northern Vancouver Island and Hecate Strait.

As a caveat, note that the anomalies for this index have been averaged across taxa groups and large spatial areas, and may therefore reflect relative rather than actual abundances. These graphs do show that the shelf area, in times of warming events, are more inundated with low nutrient gelatinous animals and the more nutritious, lipid rich zooplankton are found along the shelf break and offshore areas. For the animals relying on the spring and summer bonanza of crustaceans in the nearshore areas, this makes foraging for food a more arduous (calorie consuming) and risky (more exposure to predators) undertaking. The expectations for the years when gelatinous zooplankton are more abundant, such as 2015, equates to poor survival prospects for juvenile fish and seabirds.

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16. PACIFIC HERRING IN BRITISH COLUMBIA, 2015

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16.1. Highlights

- Biomass estimates increased in the last 2 to 6 years in 3 of the 5 main fished stocks of herring.
- Factors contributing to changes in biomass and stock status include:
    - consecutive years of below or above average recruitment;
    - increases or decreases in model estimates of natural mortality;
    - increases or decreases in mean weight-at-age;
    - changes in the spawn index or model fits to the spawn index.
- Recent increases in weight-at-age in all stocks, following declining trend during approximately 1980-2010.

16.2. Summary

Model estimates of Pacific Herring biomass, derived from a catch-age model fitted to time series data (commercial and test fishery biological samples (age, length, weight, sex, etc.), herring spawn dive survey data (spawn index), and commercial harvest data), reflect herring population trends for five major fished stocks: Strait of Georgia (SOG), west coast of Vancouver Island (WCVI), Prince Rupert District (PRD), Haida Gwaii (HG), and the central coast (CC), and two minor stocks (Area 2W and Area 27) (DFO 2015a; Figure 16-1). In 2015, a statistical catch-age model was used to provide (in part) estimates of Pacific Herring spawning biomass and age-2 recruit abundances (DFO 2015b). Herring biomass, recruit abundance, and weight-at-age are important indicators of stock status; however, there are additional considerations such as distribution of spawn. Readers are referred to DFO (2015b) for important additional information regarding the status of B.C. herring stocks.

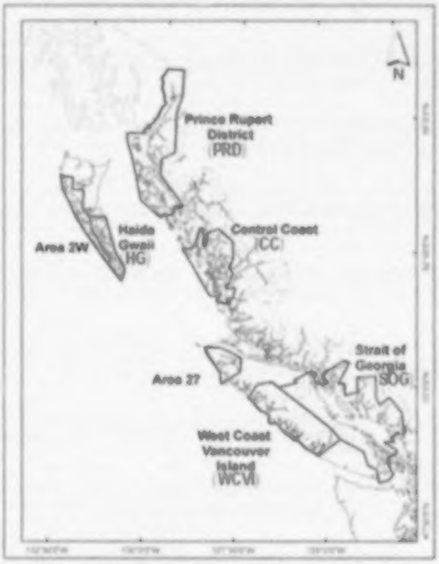

Figure 16-1. Location of the five major (Strait of Georgia, west coast of Vancouver Island, Prince Rupert, Haida Gwaii, and the Central Coast) and two minor (Area 2W and Area 27) Pacific herring fished stocks in B.C.

16.3. Status and trends

In all five major stocks of herring, there was a declining trend in weight-at-age beginning in the 1980s through 2010, with an increase or leveling off in recent years (Figure 16-2). While there were some small increases in the median spawning stock estimates from 2014 to 2015 for WCVI, the absolute magnitude of the increases was small and the uncertainty in the estimates large. Median spawning biomass for SOG herring increased from 2014 to 2015 (Figure 16-3) due in part to above average recruitment and apparent decreases in model estimates of natural mortality. Median biomass estimates for PRD herring increased during 2014-2015 due largely to increased estimate of recruitment. Median biomass estimates for HG herring decreased from 2013-2015, and recruitment in 2013 and 2015 was estimated to be below average. Median biomass estimates of CC herring increased in 2013-2015 (Figure 16-3) due to increased trends in the spawn index and decreased estimates of natural mortality.

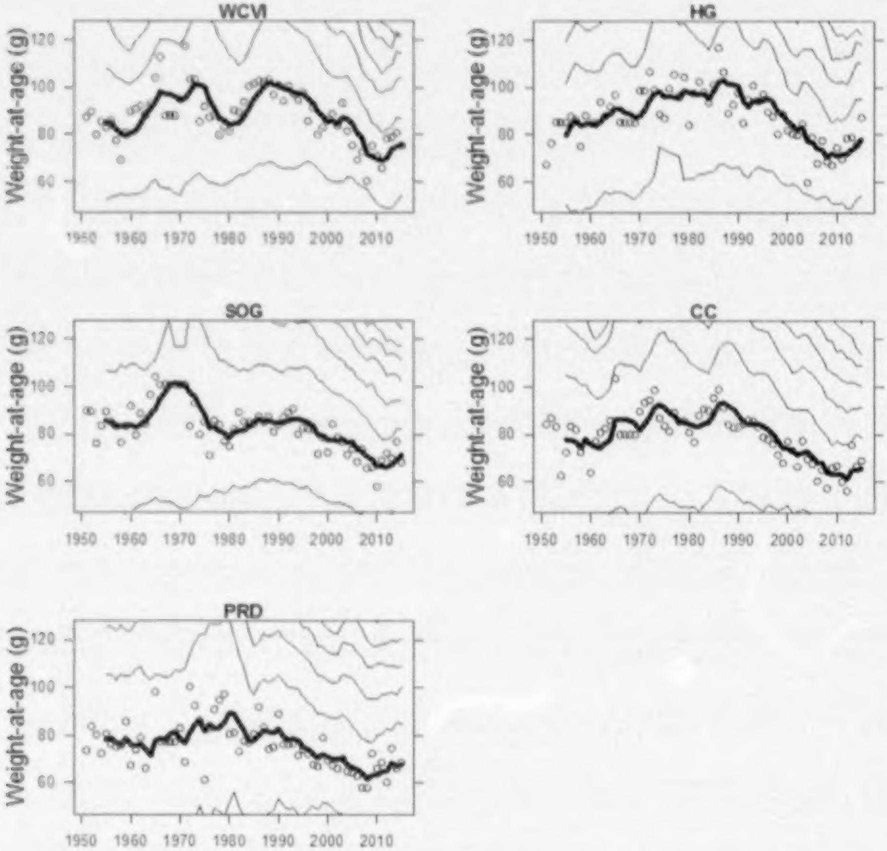

Figure 16-2. Time series of observed weight-at-age 3 (circles) and five-year running mean weight-at-age 3 (dark line) for major herring stocks, 1951-2015. Thinner black lines represent five-year running mean weight-at-age 2 (lowest) and ages 4-7 (incrementing higher from age 3). Figure from DFO (2015).

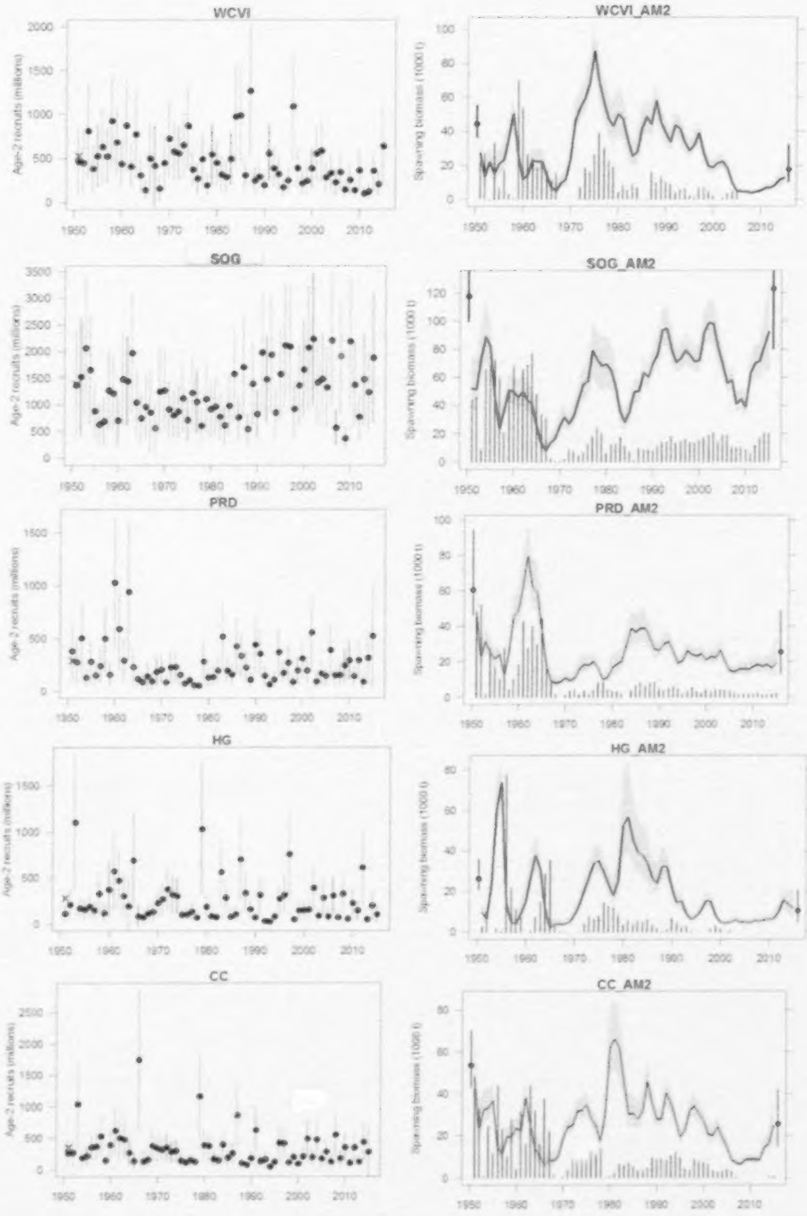

Figure 16-3. Summary of the dynamics of the five herring stocks from 1951 to 2015, where solid circles with vertical lines, and solid lines with surrounding grey envelopes, represent medians and 5-95% credible intervals. Left panels show the reconstruction of number of age-2 recruits (millions); right panels show the reconstruction of spawning biomass (SBt) for each year t, with unfished values shown at far left (solid circle and vertical lines) and the projected spawning biomass given zero catch (SB2016) shown at the far right (solid circle and vertical lines). Time series of thin vertical lines denote commercial catch (excluding commercial spawn-on-kelp). Figure adapted from DFO (2015).

16.4. Factors influencing trends in herring biomass

The biomass of Pacific Herring in three major stock areas (HG, CC and WCVI) have experienced prolonged periods of low biomass in the absence of fishing (DFO 2015). The two areas that are open to fishing maintain stable or high biomass estimates (PRD and SOG). Consideration of these biomass trends in combination with the declining trend in herring weight-at-age (with an increase in recent years) observed for all stock areas suggests that factors other than (or in addition to) fishing may be influencing herring population trends. Changes in food supply and quality, predator abundance, and competition are factors that could affect trends in herring biomass and weight-at-age (Schweigert et al. 2010, Hay et al. 2012).

Pacific Herring are zooplanktivorous, consuming primarily euphausiids (krill) and some copepods (Wailes 1936). Changes in ocean conditions, such as temperature or currents, could affect the amount and types of prey available. For example, a northerly current direction could result in the presence of California current waters off the WCVI, bringing California Current zooplankton species that have a lower energetic value, creating poorer feeding conditions for herring (Schweigert et al. 2010, Mackas et al. 2004). In addition, Tanasichuk (2012) related WCVI herring recruitment to the biomass of euphausiids.

There are a wide variety of herring predators, including Pacific Hake, Lingcod, Spiny Dogfish, Pacific Cod, Sablefish, Arrowtooth Flounder, Pacific Halibut, Steller Sea Lions, Northern Fur Seals, Harbour Seals, California Sea Lions, and Humpback Whales (Schweigert et al. 2010). Off the WCVI, fish predator abundance has decreased in recent years, while the abundance of most marine mammal predators has increased (Olesiuk 2008, Olesiuk et al. 1990). This has resulted in a relatively stable or slightly decreasing trend in the amount of WCVI herring consumed by predators since 1973 (Schweigert et al. 2010). Although a significant proportion of the herring population could be cropped annually by predation, trends in model estimates of natural mortality of WCVI herring were not found to be directly attributable to trends in estimates of predation (Schweigert et al. 2010). Herring recruitment, however, has been correlated with piscivorous hake biomass (piscivorous hake are those hake that are large enough to consume herring), suggesting predation may be an important factor influencing WCVI herring recruitment (Tanasichuk 2012).

16.5. Implications of trends

Trends in herring biomass have implications for both fisheries and predators. Pacific Herring comprise an important component of commercial fisheries in British Columbia. Fisheries Management uses forecasts of herring biomass, in conjunction with decision tables, performance metrics, and harvest rates to set total allowable catches.

Trends in herring biomass have implications for herring predators, such as fish, marine mammals and seabirds. The relative importance of herring in each predator's diet varies; however, herring may represent up to 88% of Lingcod diet (Pearsall and Fargo 2007), 40% of Pacific Cod and Pacific Halibut diets (Ware and McFarlane 1986), and 35% - 45% of pinniped diets (Olesiuk et al. 1990, Womble and Sigler 2006, Trites et al. 2007, Olesiuk 2008). Depending on the level of diet specialization and ability to switch to alternate prey, herring abundance and condition may affect predators' growth and abundance. Time series of diets of animals in this ecosystem would improve our ability to examine temporal trends in predator-prey interactions and implications of those trends.

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17. EULACHON STATUS AND TRENDS IN B.C.

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17.1. Highlights

- In 2011 COSEWIC assessed Eulachon in B.C. as three designatable units:
- Central Pacific Coast and Fraser River were assessed as endangered, and
- Nass/Skeena was assessed as Special Concern.
- From 2004 to 2014 the index of Eulachon spawning stock biomass in the Fraser River was below a 150 tonne action level but increased to above the action level in 2015.
- Eulachon catch per unit effort observations from an annual spring multispecies trawl survey were relatively high in 2013 to 2015 compared to previous years.
- In the 2015 multispecies trawl survey, there was only one mode of fish lengths where normally a bi-modal distribution is seen.
- It is unknown what factors are affecting trends in Eulachon abundance.

17.2. Description of indices

Three indices of Eulachon (*Thaleichthys pacificus)* population trends are: 1) Eulachon catches occurring in annual spring offshore multispecies trawl surveys off the west coast of Vancouver Island (WCVI, 1973-2015) and in Queen Charlotte Sound (QCS, 1998-2012); 2) commercial Eulachon catches in the Fraser (1900-2004) and Columbia (1888-2010 and 2014-2015) River systems; and 3) a spawning stock biomass estimate based on annual Fraser River Eulachon egg and larval surveys, 1995 to 2015. In the past, information from these indices was used to assess population trends and provide science advice regarding Eulachon catch recommendations. Offshore indices of juvenile Eulachon abundance, however, do not always reflect the abundance of adult Eulachon that return to rivers (Schweigert et al. 2012) and Fraser River and Columbia River commercial fisheries have been closed in recent years (except for a re-start of the Columbia commercial and recreational fishery in 2014).

17.3. Status and trends

Eulachon have experienced long-term declines in many rivers throughout their distribution from California to Alaska. COSEWIC assessed Eulachon in B.C. as three designated units (DUs): the Central Pacific coast and Fraser River DUs were assessed as endangered, and the Nass/Skeena DU was assessed as a species of special concern (COSEWIC 2011). Information in support of a recovery potential assessment (Levesque and Therriault 2011) and a recovery potential assessment (Schweigert et al. 2012) are available online. Catches in the Columbia River system decreased dramatically in the early-1990s. Columbia River Eulachon were federally-listed in the U.S.A. as threatened under the Endangered Species Act (ESA) effective May 17, 2010 and all Eulachon-directed fisheries were closed in 2011 (NOAA 2010). In 2014 and 2015 commercial and recreational fisheries in the Columbia River were re-opened on an experimental basis. The Eulachon spawning stock biomass index in the Fraser River decreased during 1994 to 2010, was below the action level (150 tonnes) during 2004 to 2014 (Hay et al. 2003), and was above the action level in 2015 (Figure 17-1). An index of biomass in the Fraser River will be estimated by an egg and larval survey in April-May 2016. Eulachon catch per unit effort observations from the spring WCVI multispecies trawl survey were the highest in recent years (2013-2015). In the 2015 WCVI multispecies trawl survey, there was one wide mode of fish lengths that was primarily <150 mm (Figure 17-2), whereas previously, annual length trends have typically been largely bimodal with a second peak at or greater than 150 mm (Figure 17-3).

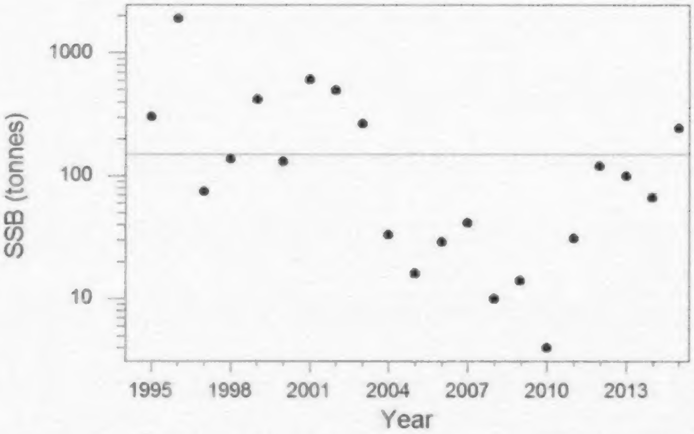

Figure 17-1. Estimated spawning stock biomass (SSB in tonnes) of Eulachon in the Fraser River, 1995-2015. Y-axis is on a log-scale. Horizontal pink line shows the 150 tonne action level.

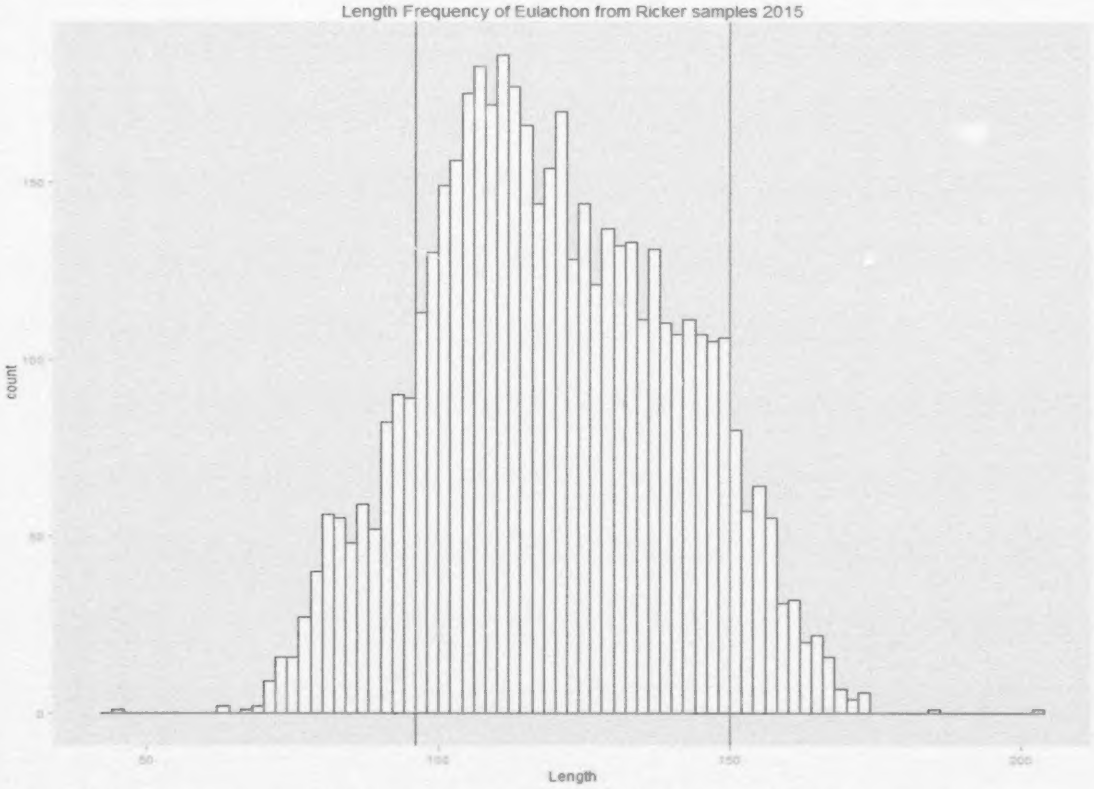

Figure 17-2. Length frequency histograms (in mm) of Eulachon measured off the west coast of Vancouver Island in early May, 2015. Blue and red vertical lines are estimated bi-modal means from all Eulachon from all survey years (1995-2015).

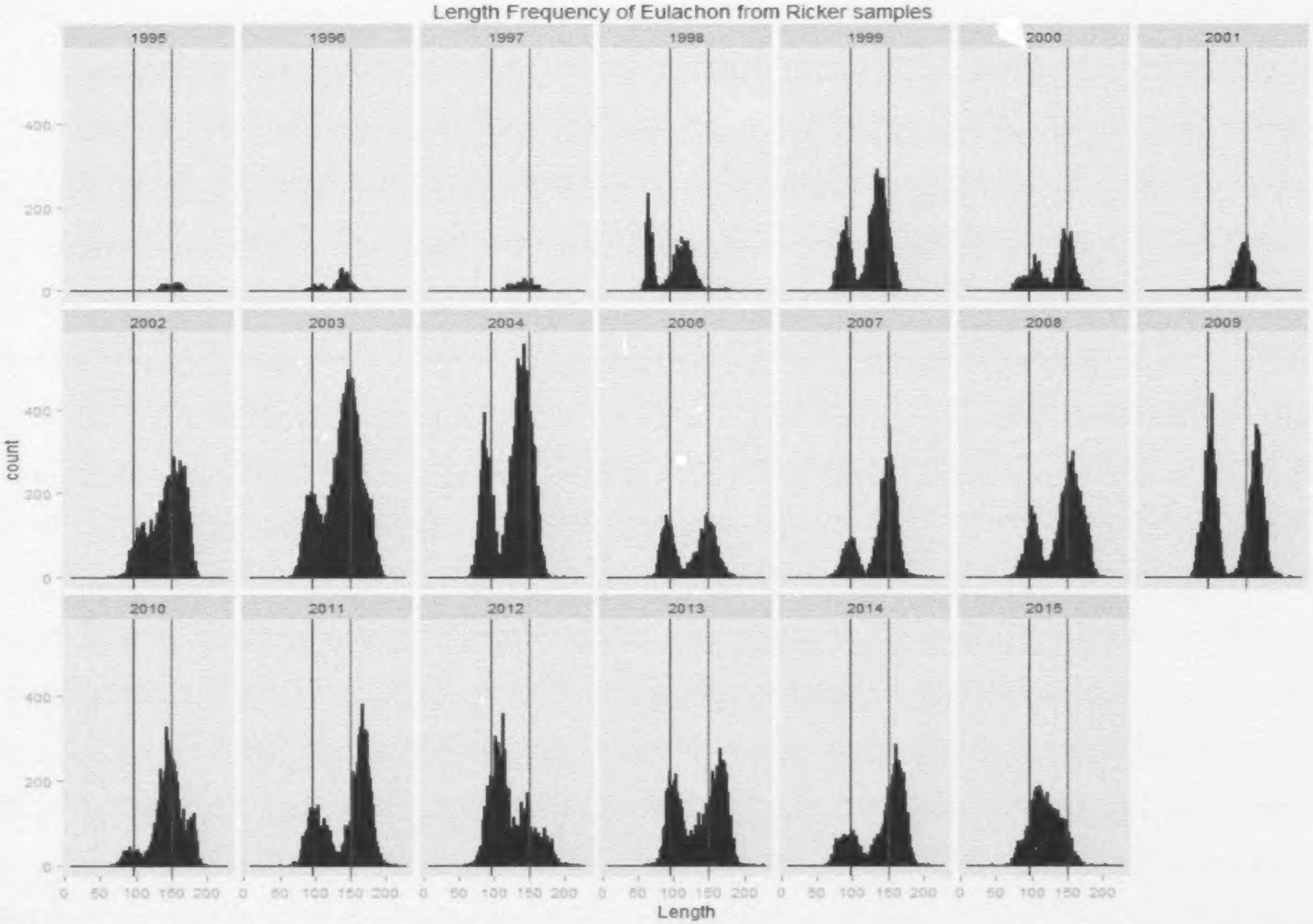

Figure 17-3. Length frequency histograms (in mm) of Eulachon by year from WCVI samples. Blue and red vertical lines are estimated bi-modal means from all Eulachon from all survey years (1995-2015).

17.4. Factors causing those trends

It is unknown what caused the declining trends in Eulachon abundance in recent years. Schweigert et al. (2012) state that "No single threat could be identified as most probable for the observed decline in abundances among DUs [designatable units] or in limiting recovery. However, mortality associated with coastwide changes in climate, fishing (direct and bycatch) and marine predation were considered to be greater threats at the DU level, than changes in habitat or predation within spawning rivers."

Also, DFO (2015) states that "Some existing threats are unlikely to have been responsible for recent declines (e.g., food, social and ceremonial (FSC) fisheries, marine mammal predation, and degradation of freshwater habitat) but may now be preventing recovery from low population abundance.". The increase in 2015 spawning biomass may be attributed to favourable juvenile and marine survival in 2012 to 2015, which is consistent with trawl survey catch per unit effort and length frequency observations. There is uncertainty as to the cause of the lack of a bi-modal distribution in fish lengths observed in the 2015 trawl survey. That observation may reflect low catch rates of older cohorts typically observed and/or reduced growth of those cohorts.

17.5. Implications of those trends

Reduced biomass of Eulachon has negative implications for First Nations and commercial fishers. Eulachon are socially and culturally significant to First Nations and are harvested by First Nations at low levels. Recreational and commercial fisheries are currently closed.

Reduced Eulachon abundance also likely has negative impacts on their predators. Important predators of Eulachon include: marine mammals (particularly seals and sea lions in the estuaries, and porpoises), Chinook and Coho Salmon, Spiny Dogfish, Pacific Hake, White Sturgeon, Pacific Halibut, Walleye Pollock, Sablefish, rockfish, Arrowtooth Flounder, and others (Levesque and Therriault 2011). Diet data time series of all animals in the ecosystem would improve our ability to examine temporal trends in predator-prey interactions and the implications of those trends.

17.6. References

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18. LA PEROUSE ACOUSTIC-TRAWL SURVEY

Jennifer Boldt[1], Stéphane Gauthier[2], Matt Thompson[1], Linnea Flostrand[1], Vanessa Hodes[1], and Jessica Nephin[2]

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18.1. 2015 Highlights

- In 2015 relative to previous years, herring were distributed more broadly throughout the La Perouse study area, including the southern area. Herring were also distributed further offshore and in areas with fewer hake.
- There were more hake in the La Perouse area than previous years.
- Age-1 hake, not seen in recent years, were observed in the southern portion of the survey area.

18.2. Description

The La Perouse Bank, off the west coast of Vancouver Island (WCVI), is a highly productive area within the coastal upwelling zone between North Vancouver Island and California that supports valuable commercial fisheries. Wind-induced upwelling results in high primary production and high euphausiid biomass. Both WCVI and Strait of Georgia (SOG) stocks of adult and juvenile (age-2+) Pacific Herring forage in the La Perouse Bank area in summer months before adult herring migrate to nearshore spawning areas in the winter and early spring. Year round residents and predators (e.g. Sablefish, Pacific Cod, Harbour Seals, and Steller Sea Lions) and part-time predators (e.g. Pacific Hake, Chinook Salmon, Coho Salmon, Pacific Mackerel, Humpback Whales, Northern Fur Seals, California Sea Lions) as well as fishers take advantage of this highly productive area. The abundance of herring prey and predators occupying the La Perouse Bank varies annually and can be affected by several biotic and abiotic factors, which are not entirely understood.

The main goal of the La Perouse acoustic-trawl survey is to understand factors affecting the distribution, relative abundance, and trophodynamics of pelagic fish (especially herring) and prey species (small fish, zooplankton). The operational objectives include examining the relative abundance and distribution of pelagic fish in an area where herring have historically aggregated in the summer. In addition to fish species composition and biological information, zooplankton distribution, relative abundance, biomass, and species composition data are collected. In addition, water property data, such as conductivity, temperature, density, and oxygen are collected.

Scientific echosounders are valuable fishery-independent tools that have been used to determine the spatial distribution and biomass of animals, including herring (Thomas and Thorne 2003) and hake (Fleischer et al. 2008). Acoustic data were collected along parallel transects in a core survey area off the southwest coast of Vancouver Island (Figure 18-1). The area was bounded inshore by approximately the 50 m isobath and bounded offshore in the south and west by the 200 m isobath (general maximum depth distribution of herring). The northern boundary was based on historical surveys and known distributions of herring. Transect locations were placed from a random starting point and spaced 6 nmi apart. A second set of transects was offset from the first set by half the distance between transects. Data were collected along extra transects north of the core survey area to explore the validity of the northern boundary.

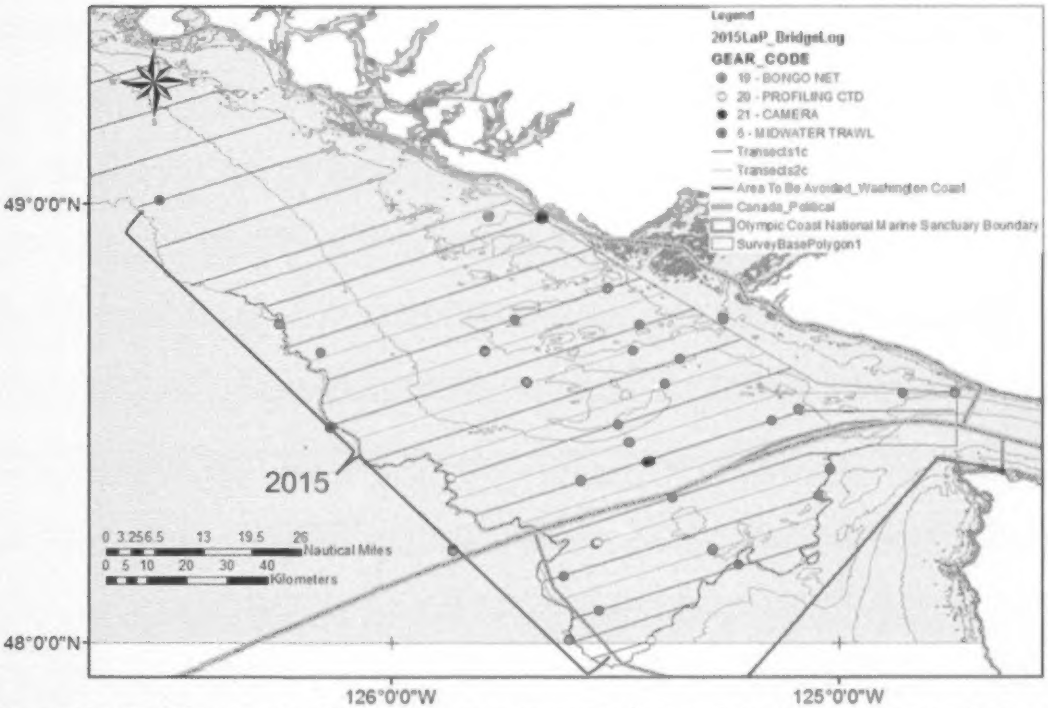
Legend
2015LaP_BridgeLog
GEAR_CODE
● 19 - BONGO NET
○ 20 - PROFILING CTD
● 21 - CAMERA
● 6 - MIDWATER TRAWL
Transects1c
Transects2c
Area To Be Avoided_Washington Coast
Canada_Political
Olympic Coast National Marine Sanctuary Boundary
SurveyBasePolygon1
49°0'0"N
48°0'0"N
126°0'0"W
125°0'0"W
2015
0 3.25 6.5 13 19.5 26 Nautical Miles
0 5 10 20 30 40 Kilometers

Figure 18-1. La Perouse acoustic-trawl survey area (purple line), with two sets of transects (green and black lines). Stations where midwater trawl samples were collected (green dots), and CTD and zooplankton data were collected (red dots; note that CTD and zooplankton were done at the same locations, so the light green CTD dots do not show up in the figure). In 2015, all transects in the core area were completed in addition to 3 transects north of the core survey area.

Acoustic data were collected with a SIMRAD EK60 scientific echo sounder operating at 18 kHz, 38 kHz, and 120 kHz. Acoustic echosign was verified using a midwater trawl net (which was often equipped with net cameras to help identify specific layers in the water column) to collect small representative samples of animals. Trawl net catch per unit effort and catch weight and composition were recorded. In addition, catches were sorted to species and total catch or subsamples of each species were measured, weighed, and stomach contents were examined. Species composition and fish size data were used to apportion acoustic backscatter data. Backscatter was converted to biomass estimates for some species (where target strength information was available). Biomass of herring, hake, and age-1 hake are shown here; however, other species are also observed in this survey.

18.3. Status and trends

During July 23 to August 2, 2015, all transects in the core area were completed in addition to 3 transects north of the core survey area. Herring were distributed throughout much of the survey area and there were more herring observed along the first set of transects compared to the second set (Figure 18-2). Herring were observed in net samples along with hake; however, in areas where hake were caught, there were far fewer herring than in areas without hake. For both sets of transects, age-1 hake (which had not been observed in recent years) were observed in the southeast; adult hake were observed in the southern and mid-offshore sections of the survey area (Figure 18-2).

In 2015, there were more herring and hake observed than in previous years (2013-2014; Figure 18-3). Also, in 2015, herring appeared to have a broader distribution than in previous years (i.e. distributed throughout the survey area including the south) and perhaps were further offshore than in previous years (Figure 18-3).

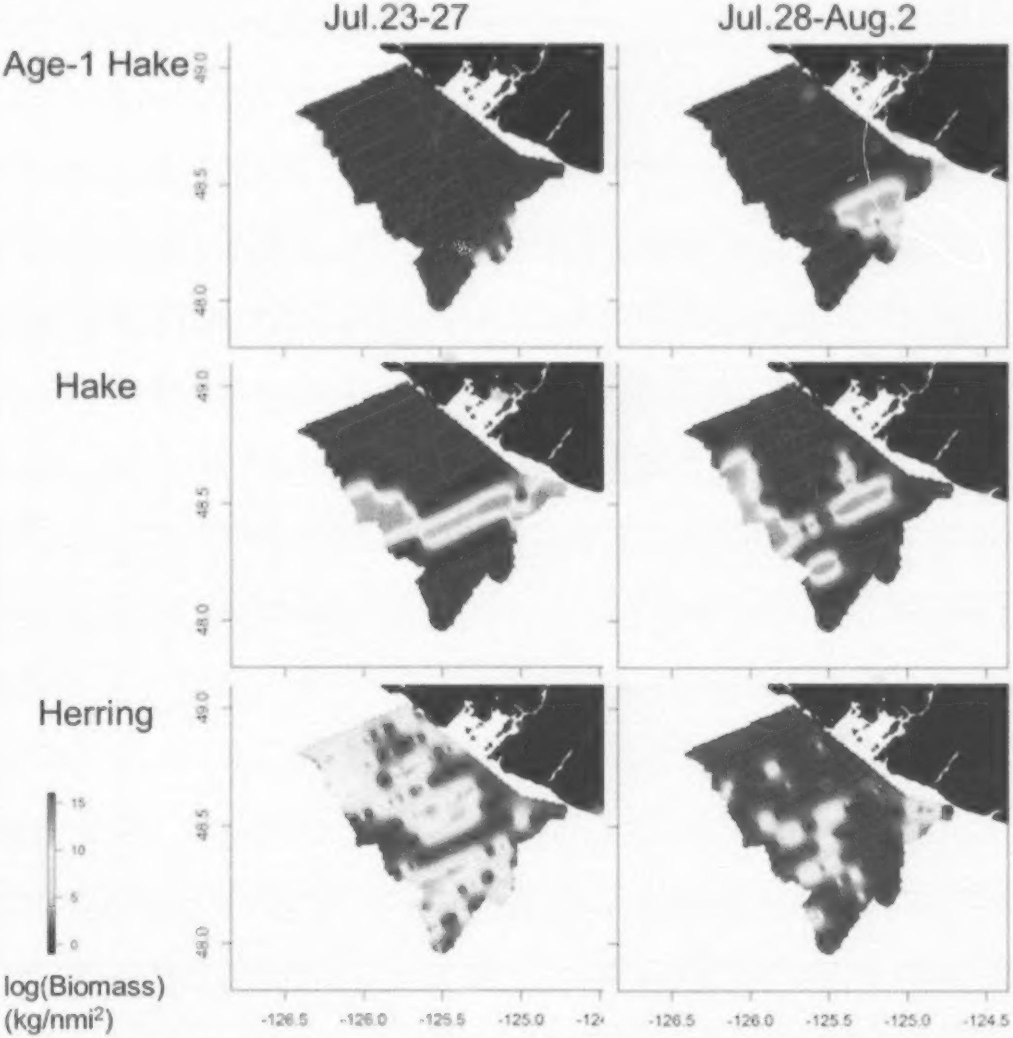
Jul.23-27
Jul.28-Aug.2
Age-1 Hake
Hake
Herring
49.0
48.5
48.0
15
10
5
0
log(Biomass)
(kg/nmi²)
-126.5
-126.0
-125.5
-125.0
-12
-126.5
-126.0
-125.5
-125.0
-124.5

Figure 18-2. Biomass distribution of age-1 hake, adult hake, and herring from the La Perouse acoustic-trawl core survey area during 2015 for both sets of transects completed during July 23-27 and July 28-August 2. Light grey lines indicate transect locations. Colour scale indicates log-transformed biomass (kg/nmi^2).

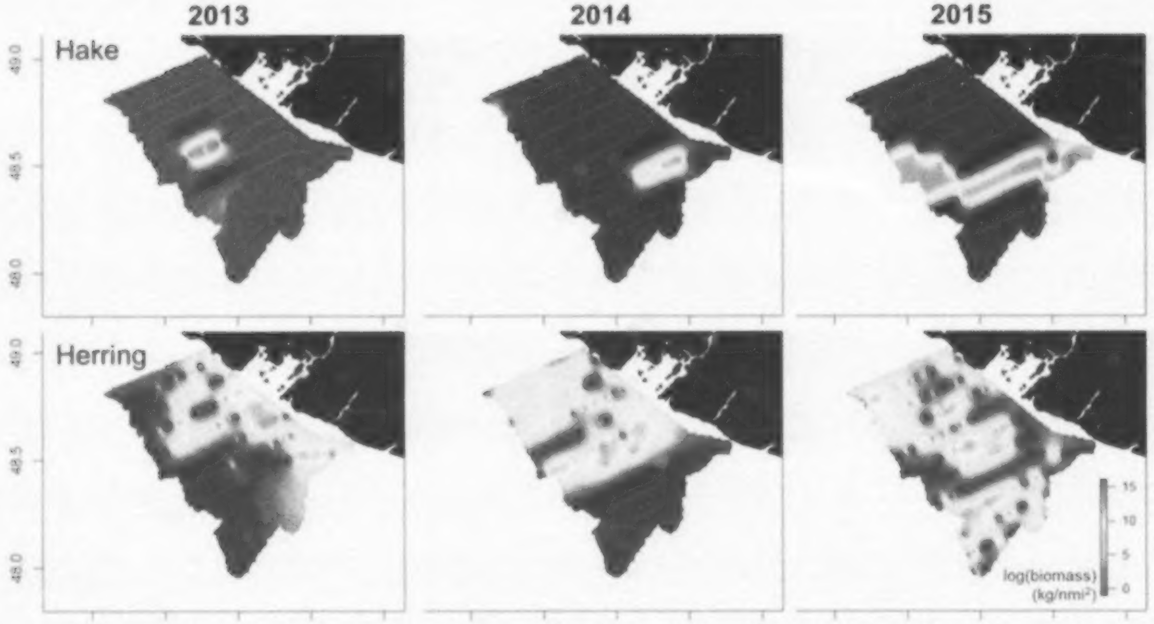

Figure 18-3. Biomass distribution of adult hake and herring from the La Perouse acoustic-trawl core survey area during 2013-2015 for one set of transects. Light grey lines indicate transect locations. Colour scale indicates log-transformed biomass (kg/nmi²).

18.4. Factors causing trends

Factors that can potentially affect fish abundance and distribution include prey availability (including timing), predator and competitor species abundance, environmental factors, and disease. For example, herring recruitment and survival has been linked to water temperatures (Tester 1948, Ware 1991) and bottom-up control of production (Ware and Thompson 2005, Perry and Schweigert 2008, Schweigert et al. 2013). Changes in ocean conditions, such as temperature or currents, could affect the amount and types of prey available. For example, a northerly current direction could result in the presence of California Current waters and, hence zooplankton species that have a lower energetic value, creating poorer feeding conditions for herring (Schweigert et al. 2010, Mackas et al. 2004). In addition, Tanasichuk (2012) related WCVI herring recruitment to the biomass of euphausiids.

There are a wide variety of herring predators, including Pacific Hake, Lingcod, Spiny Dogfish, Pacific Cod, Sablefish, Arrowtooth Flounder, Pacific Halibut, Steller Sea Lions, Northern Fur Seals, Harbour Seals, California Sea Lions, and Humpback Whales (Schweigert et al. 2010). Off the WCVI, herring recruitment has been correlated with piscivorous hake biomass (piscivorous hake are those hake that are large enough to consume herring), suggesting predation may be an important factor influencing WCVI herring recruitment (Tanasichuk 2012).

18.5. References

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19. WCVI MULTI-SPECIES SMALL-MESH BOTTOM TRAWL SURVEYS (TARGET SPECIES: SMOOTH PINK SHRIMP)

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19.1. Highlights

- Smooth Pink Shrimp biomass in Areas 124-125 in 2015 declined from the peak in 2014, but remained among the highest observed (since surveys began in 1973).
- Among the well-sampled fish taxa, Walleye Pollock and Pacific Halibut also had record high biomass in this survey in 2014, and their biomass also declined in 2015 to near-normal amounts.
- Based on the species composition of the "well-sampled" taxa, the years 2014 and 2015 clustered together but weakly with 2010-2013, possibly indicating a changing species composition.
- Chronological clustering of years based on large-scale climate indices shows some relationship with year-clusters of well-sampled taxa off WCVI.

19.2. Background

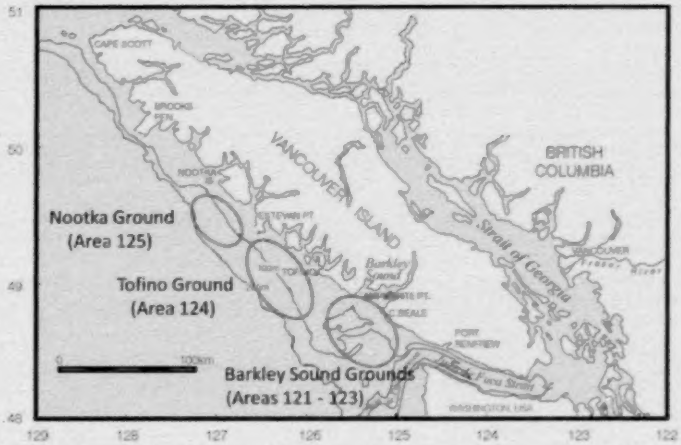
51
50
49
48
129
128
127
126
125
124
123
122
CAPE SCOTT
BROOKS PEN.
NOOTKA IS.
ESTEVAN PT.
TOFINO
VANCOUVER ISLAND
BRITISH COLUMBIA
Strait of Georgia
VANCOUVER
Fraser River
Barkley Sound
C. BEALE
PORT RENFREW
Juan de Fuca Strait
WASHINGTON, USA
Nootka Ground
(Area 125)
Tofino Ground
(Area 124)
Barkley Sound Grounds
(Areas 121 - 123)
0
100km

Figure 19-1. Map showing the three main shrimp (Pandalus jordani) fishing grounds and survey areas off Vancouver Island (red ovals). The Nootka (Area 125) and Tofino (Area 124) Grounds are the northern and middle ovals, respectively, and have been surveyed since 1973. The southern oval represents the shrimp fishing grounds off Barkley Sound, surveyed since 1996.

Fishery-independent bottom trawl surveys using a small-mesh net (targeting the Smooth Pink Shrimp *Pandalus jordani*) have been conducted during May since 1973 in two regions, and since 1996 in three regions, off the west coast of Vancouver Island (Figure 19-1). The survey masks for these regions, over which the total biomass of each species has been estimated, generally occur between the 100 m and 200 m isobaths for Areas 124 and 125.

This small-mesh bottom trawl survey was designed to target Smooth Pink Shrimp on the shrimp fishing grounds in a relatively small area off the west coast of Vancouver Island. The interannual variability of biomass estimates of other taxa caught along with Smooth Pink Shrimp depends on whether these other taxa are highly mobile in and out of the survey area or are highly patchy in their distribution. An autocorrelation analysis indicates that of the 36 taxa regularly sampled and identified to species on this survey, 16 of them appear to be well-sampled (i.e. have positive autocorrelations of at least a one year lag; Table 19-1). Of those species shown in Figure 19-2, all are well-sampled by this survey except for Spiny Dogfish, Pacific Hake, and English Sole.

19.3. Results for 2015

Pelagics	Demersals		Benthics
Pacific hake	Silvergrey rockfish	Pacific cod	Sea mouse
American shad	Darkblotch rockfish	Sablefish	Heart urchin
Pacific herring	Green rockfish	Lingcod	Sea urchins
Eulachon	Yellowtail rockfish	Ratfish	Sea cucumber
Dogfish	Boccacio	Smooth pink shrimp	
Walleye pollock	Canary rockfish	Dover sole	
	Redstripe rockfish	Pacific sanddab	
	Pacific Ocean perch	Petrale sole	
	Arrowtooth flounder	Rex sole	
	English sole	Flathead sole	
	Pacific halibut	Slender sole	
	Yelloweye rockfish	Spot Prawn	

Blue taxa names represent no significant autocorrelations

Table 19-1. List of 'core' species which have been sampled and identified routinely during these small mesh surveys since 1973 and for which annual biomass estimates are calculated. Taxa in black are those with significant ($p<0.05$) autocorrelations and which are therefore considered to be "well-sampled" by this survey.

Surveys in May 2015 found the biomass of *Pandalus jordani* shrimp off central Vancouver Island had declined from the record high level observed in 2014 (Figure 19-2), but remained among the highest recorded since 1973. The biomass of Pacific Halibut, English Sole, and Walleye Pollock, which had also been at recorded observed highs in 2014, also declined in 2015 to more normal (but still high) levels (Figure 19-2).

Based on the well-sampled taxa, survey years from 1973 to 2015 were clustered to identify years with similar taxonomic compositions, using a chronological clustering method. Results indicate seven significant clusters, with one outlier year (2002). The largest composition change separated 1996 and prior years from 1997 and subsequent years (Figure 19-3). The years 2014 and 2015 clustered together, but only weakly with 2010-2013, which may indicate changing species composition in 2014-15 from 2010-2013. A bubble plot (Figure 19-4) identifies why 2002 is an outlier (high relative abundances for many taxa), and why 2014 and 2015 are different from other year groups.

A large number of climate indices were extracted from the internet (http://www.esrl.noaa.gov/psd/data/climateindices/list/) and screened for multicolinearity. Climate indices were then selected to be uncorrelated and representative of climate conditions in the North Pacific: El Niño index (Niña3.4), North Pacific Index, North Pacific Gyre Oscillation Index, Pacific Decadal Oscillation Index, Southern Oscillation Index. These were clustered using the same chronological clustering technique, to see whether climate indices might explain the clusters of species from the west coast Vancouver Island multi-species trawl survey (Figure 19-6). The relationship between cluster 'boundaries' in climate and species indices is suggestive, with more years in which climate boundaries occurred prior to (i.e. led) species composition changes (Figure 19-5). More work is needed to clarify these relationships.

Conclusions from this analysis are the following:

- Smooth Pink Shrimp biomass in Areas 124-125 in 2015 declined from the peak in 2014, but remained among the highest observed (since surveys began in 1973);
- among the well-sampled fish taxa, Walleye Pollock and Pacific Halibut also had record high biomass in this survey in 2014, and their biomass also declined in 2015 to near-normal amounts;
- species composition of the "well-sampled" taxa in 2014 and 2015 clustered together but weakly with the composition during 2010-2013, suggesting a possible change in species composition;
- surveyed biomass of well-sampled taxa has generally increased since 2010 compared with 2006-2009 (see Figure 19-4); and
- chronological clustering of years based on large-scale climate indices shows some relationship with year-clusters of well-sampled taxa off WCVI, but details remain to be clarified.

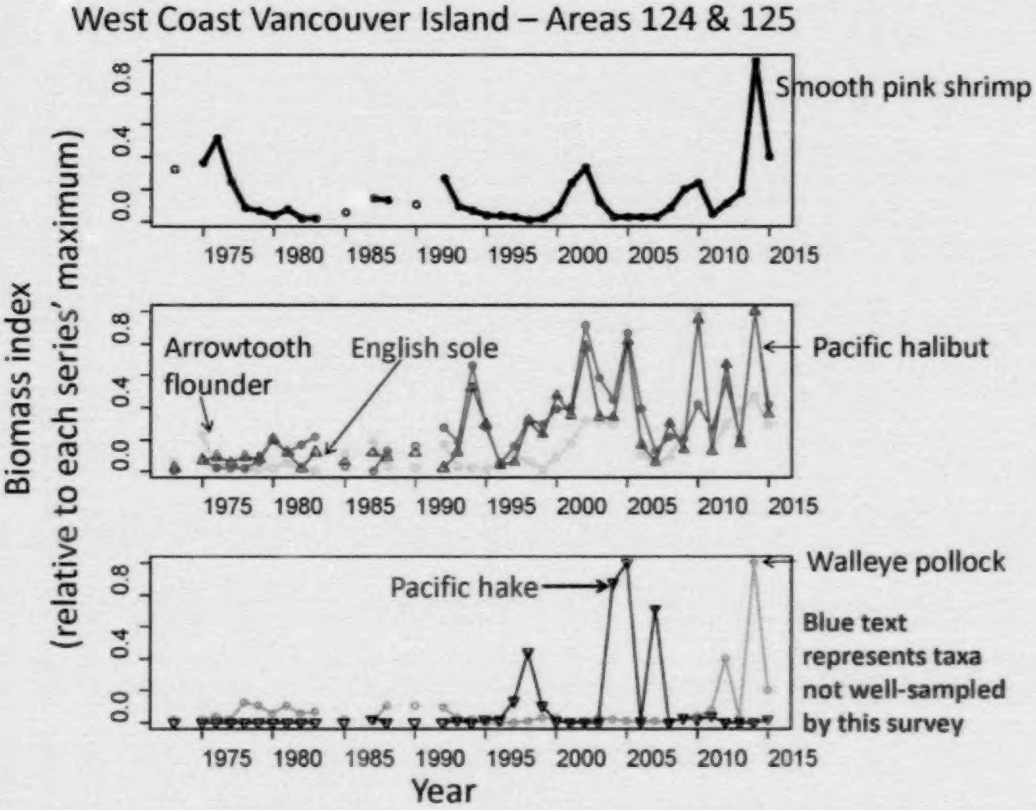

Figure 19-2. Time series of normalised (to maximum biomass) survey catches in Areas 124 and 125 of Smooth Pink Shrimp, Spiny Dogfish, Pacific Halibut, Arrowtooth Flounder, English Sole, Pacific Hake and Walleye Pollock. Sampling was conducted in May of each year. Blue text identifies those taxa believed to be not well-sampled by the survey, based on an autocorrelation analysis.

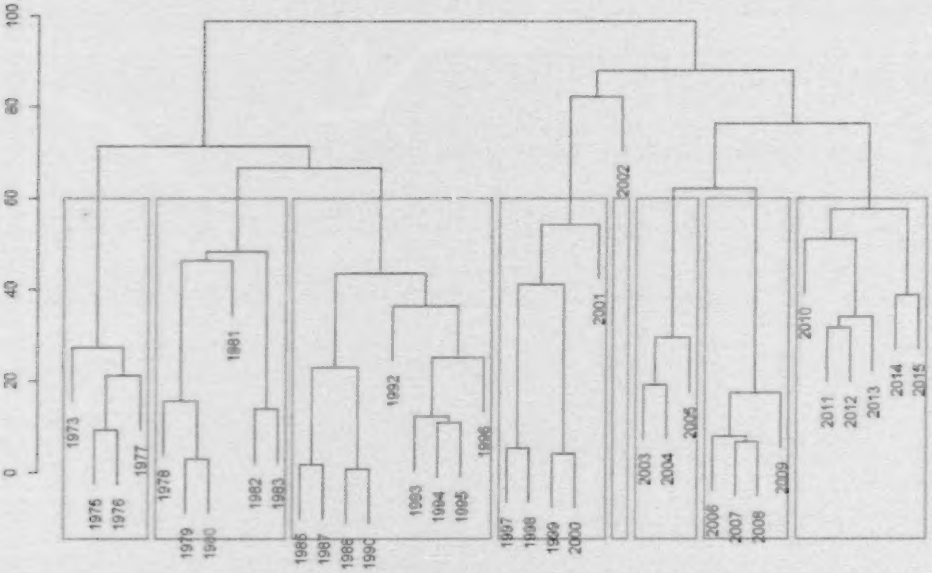

Figure 19-3. Dendrogram of years and clusters based on biomasses of well-sampled taxa (black font taxa in Table 19-1) using a chronological clustering method. The largest break separated clusters in 1996 and prior years from 1997 and subsequent years. Sampling was conducted in May of each year. Significant (defined by a randomisation procedure) year clusters are identified for 1973 – 1977; 1978 – 1983; 1985 – 1996; 1997 – 2001; 2002; 2003 – 2005; 2006 – 2009; 2010 – 2015 (red boxes).

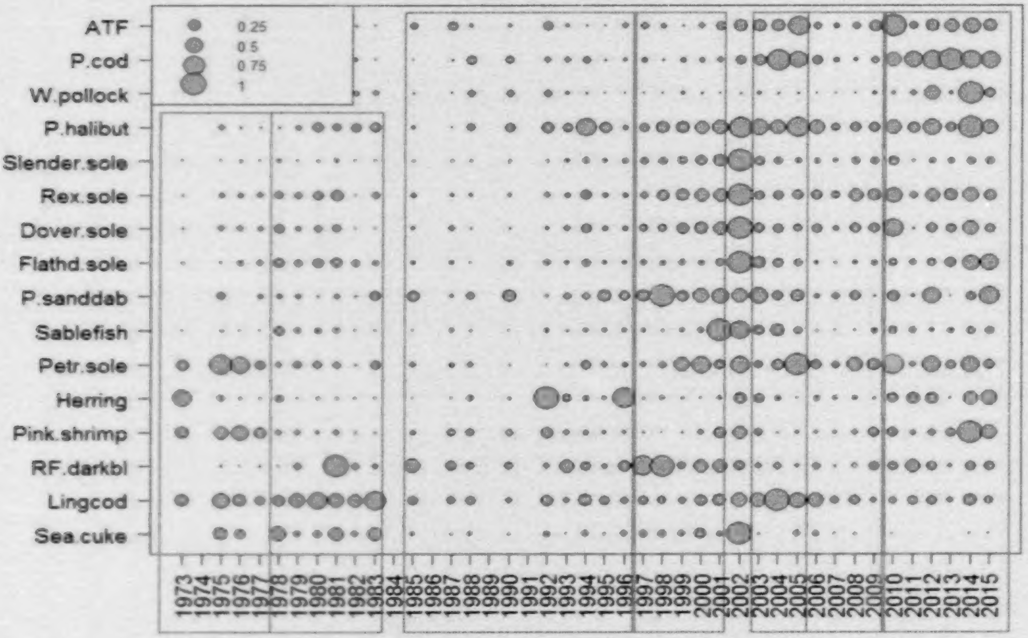

Figure 19-4. Bubble plot of well-sampled taxa (black text taxa in Table 19-1), showing relative abundances by year (abundances scaled to series maximum, as in Figure 19-2). The red boxes identify the significant clusters from Figure 19-3.

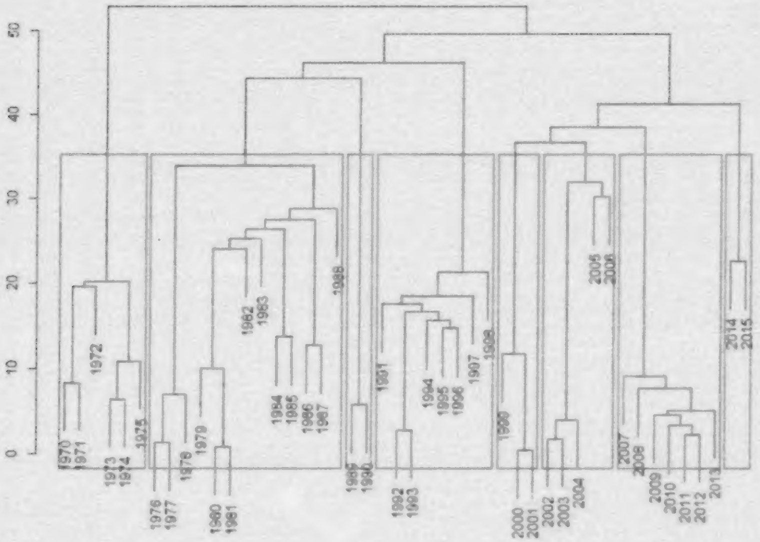

Figure 19-6. Dendrogram of years and clusters based on large-scale climate indices for the Pacific Ocean from 1970 to 2015, using a chronological clustering technique. The climate indices were the El Niño index (Niña3.4), North Pacific Index, North Pacific Gyre Oscillation Index, Pacific Decadal Oscillation Index, Southern Oscillation Index. Significant clusters as defined by a randomisation test are outlined in red boxes.

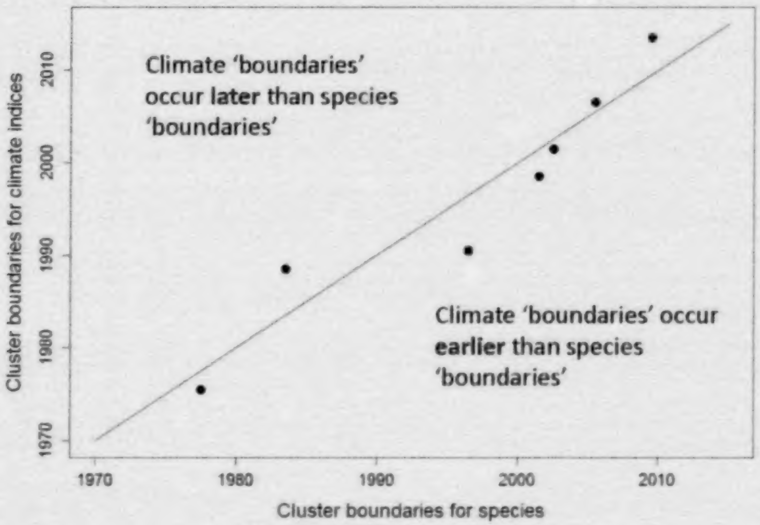

Figure 19-5. Comparison of cluster 'boundaries' (i.e. years which separate clusters) from the species analysis (X-axis) and the climate analysis (Y-axis). Diagonal line is the 1:1 line, not a regression line.

20. 2015 GROWTH OF JUVENILE COHO SALMON OFF WCVI WAS ABOVE AVERAGE

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20.1. Highlights

- 2015 growth of juvenile Coho Salmon off the west coast of Vancouver Island was above average, foretelling high survival for the cohort.
- For the 2015 ocean entry year, physical indicators predict lower smolt survival, opposite to that being predicted from biological indicators.

20.2. Summary

Integrated pelagic ecosystem surveys for juvenile salmon and ocean conditions (physical/biological) salmon have been used to assess the distribution, growth, condition and survival of Pacific Salmon in different parts of the British Columbia coastal ecosystem since 1998. These surveys are usually conducted in late spring-early summer (June-July) and in the fall (October-November). This work assumes that smolt survival will be higher in years when salmon are growing rapidly and are in good condition than in years of low growth and poor condition. Hence, smolt survival is expected to be positively correlated to indicators of juvenile salmon growth rate (Trudel et al. 2008).

Since 1998, growth rates of juvenile Coho Salmon during the summer season off of the west coast Vancouver Island (WCVI) have been estimated using samples collected in the fall (Trudel et al. 2008). The lowest growth observed in the time series occurred in 2005 followed by 1998 (Figure 20-1), which were also the two warmest years of the time series (Table 20-1). Interestingly, the highest growth of the time series was observed in 2014, also an unusually warm year. In 2015, growth rates of juvenile Coho Salmon off WCVI were above average (Figure 20-1) despite that sea surface temperature was one of the highest on record (Table 20-1). This suggests that the interannual variation in the growth rates of juvenile Coho Salmon is not mediated by changes in sea surface temperature within the range observed between 1998 and 2015.

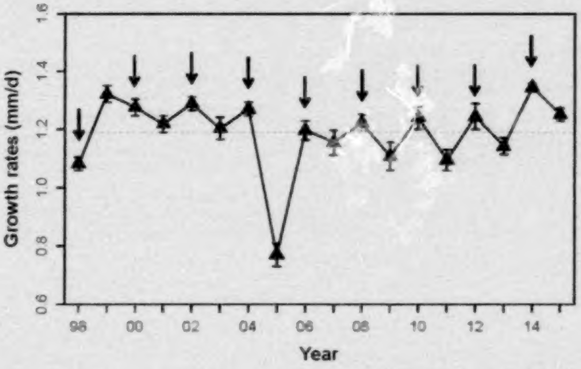

Figure 20-1. Growth rates (May-October) of juvenile Coho Salmon off the west coast of Vancouver Island. The red dotted line represents the 1998-2015 average. The error bars are 2 times the standard error. Even years are indicated by a downward arrow. Details on the procedure used to estimate growth rate are provided in Trudel et al. (2007).

The above average growth rates observed for juvenile Coho Salmon off the west coast of Vancouver Island in 2015 suggest that smolt survival will also be high for that year (Figure 20-2). In contrast, predictions based on physical indices such as the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO), and sea surface temperature (SST) indicate the opposite, i.e. low smolt survival (Figure 20-2). Similar predictions were made for the 2014 ocean entry year (Trudel et al. 2015). Clearly, one of these relationships is bound to break given that their predictions are at the opposite end of the spectrum (very high vs. very low). Preliminary estimates of smolt survival for WCVI Coho Salmon that went to sea in 2014 were in the order of 5% (S. Baillie, unpublished). This suggests that the 2015 winter conditions were not favourable to survival despite high growth in 2014. It is unclear if a similar pattern will occur with the 2015 ocean entry year as well.

Table 20-1. Physical and biological indicators of smolt survival for WCVI Coho Salmon. PDO: Pacific Decadal Oscillation (averaged between May and September); NPGO: North Pacific Gyre Oscillation Index (averaged between May and September); ENSO: El Niño Southern Oscillation Index (averaged between May and September); Mean SST: Sea Surface Temperature at Amphitrite point (averaged between March and June); WCVI Coho Summer Growth: Growth of juvenile Coho Salmon from ocean entry to the Fall (October-November). Ocean conditions are ranked from best (rank 1; green) to worst (rank 18; red) for Coho Salmon. Note that ocean conditions off WCVI were generally favourable to Coho Salmon in 1999-2001 and 2008, and not favourable during the 1998 El Niño, and in 2005-2006.

RANK SCORES **Environmental Variables**	***98***	***99***	***00***	***01***	***02***	***03***	***04***	***05***	***06***	***07***	***08***	***09***	***10***	***11***	***12***	***13***	***14***	***15***
PDO (May-Sep)	10	4	6	5	11	15	14	16	12	13	2	9	7	3	1	8	17	18
NPGO (May-Sep)	14	5	3	1	8	10	13	18	15	9	2	11	6	7	4	12	16	17
ENSO (May-Sep)	12	2	7	8	16	9	11	10	13	3	6	15	1	4	14	5	17	18
Mean SST - WCVI (Amphitrite) - Mar-Jun	16	1	8	3	4	12	15	17	11	5	6	9	13	10	2	7	14	18
WCVI Coho Summer Growth	17	2	4	10	3	11	5	18	12	13	9	15	8	16	7	14	1	6
Mean Rank	13.8	2.8	5.6	5.4	8.4	11.4	11.6	15.8	12.6	8.6	5.0	11.8	7.0	8.0	5.6	9.2	13.0	15.4
Rank of Mean Ranks	16	1	4	3	8	11	12	18	14	9	2	13	6	7	4	10	15	17

Data Sources:
PDO: http://jisao.washington.edu/pdo/PDO.latest
NPGO: http://www.o3d.org/npgo/data/NPGO.txt
ENSO: http://www.esrl.noaa.gov/psd/enso/mei/table.html
Amphitrite SST: http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/data/amphitrt.txt

Interestingly, juvenile Coho Salmon growth has generally been higher in even years than odd years since 2001, and this pattern continued in 2015 (Figure 20-1). An odd-even year pattern is also apparent in the residuals of the smolt survival and PDO, SST, and NPGO relationships, with higher survival observed in even years (Figure 20-2). The underlying mechanism generating this pattern is unclear at this point. In marine waters of southern British Columbia, juvenile Pink Salmon are typically most abundant in even years (Beamish et al. 2008, Irvine et al. 2014). However, they rarely occur off WCVI during summer, and are only present in moderate numbers during fall in even years. One possibility is that juvenile Coho Salmon compete with adult Fraser River and Puget Sound Pink Salmon when they return in coastal waters in the summer of odd years.

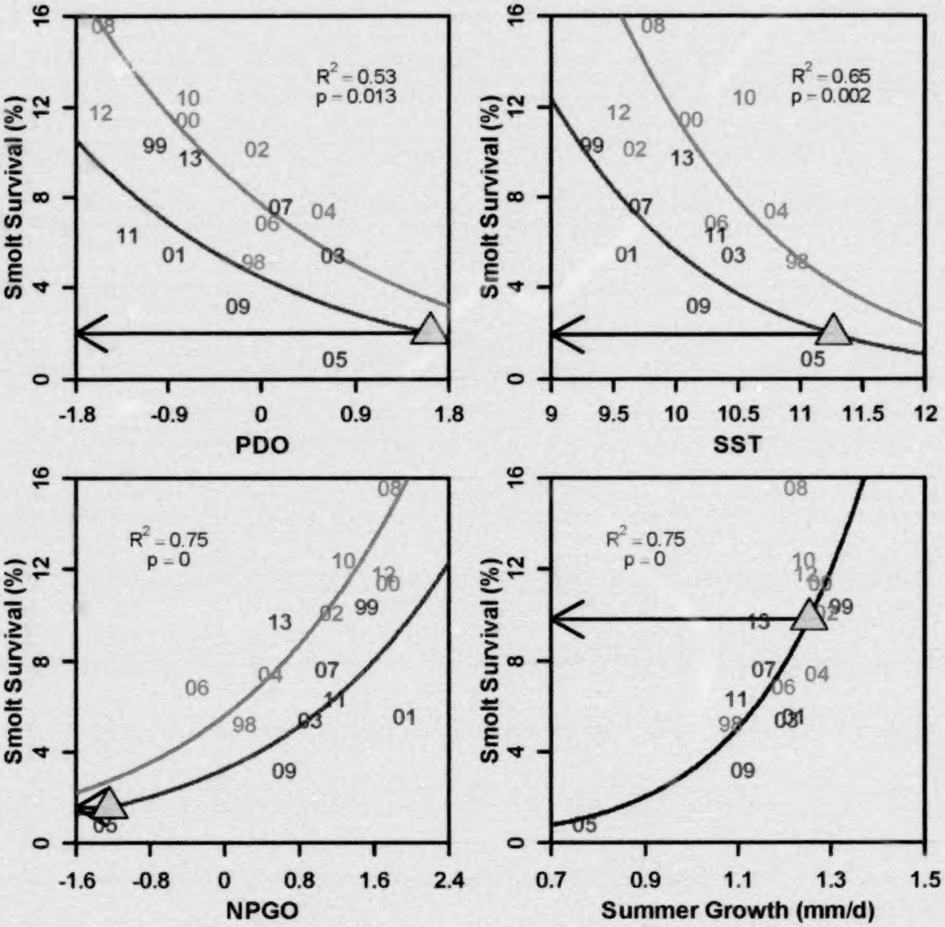

Figure 20-2. Correlations between survival of Robertson Creek Coho Salmon smolts with the Pacific Decadal Oscillation (PDO; May-September average), sea surface temperature off Amphitrite Point on the west coast of Vancouver Island (SST; March-June average), North Pacific Gyre Oscillation (NPGO; May-September average), and juvenile Coho Salmon growth off the west coast of Vancouver Island (May-October). The numerical symbols represent the ocean entry year. Odd years are in blue, even years are in red. The green triangle represents the predicted value for the 2015 ocean entry year.

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21. 2015 DISTRIBUTION AND ABUNDANCE OF PACIFIC HAKE (MERLUCCIUS PRODUCTUS)

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21.1. Highlights

- The 2015 Pacific Hake biomass estimate of 2.156 mmt is the highest in the history of the survey.
- Pacific Hake distribution did not extend further than the northern end of Vancouver Island, with the exception of faint scattering on the western side of Haida Gwaii.
- Pacific Hake were found in abundance along the Vancouver Island coast.
- Significant aggregations of age-1 hake were observed in the southern end of Vancouver Island.

21.2. Summary

Pacific Hake is a semi-pelagic, schooling species of fish that is found along the Pacific coast of North America. It ranges from southern California to northern British Columbia (25-55 °N). It is a migratory species that is thought to spawn off of the southern to central California coast during January to March (Saunders and McFarlane 1997). Adult hake then migrate north in the spring and by the summer can be detected in large aggregations from Northern California to the northern end of Vancouver Island, with distributions sometimes exceeding these boundaries. Size and age generally increase with increasing latitude during the migratory season. The population of Pacific Hake found in the Strait of Georgia and Puget Sound are genetically distinct and not included in this survey (Iwamoto et al. 2004, King et al. 2012).

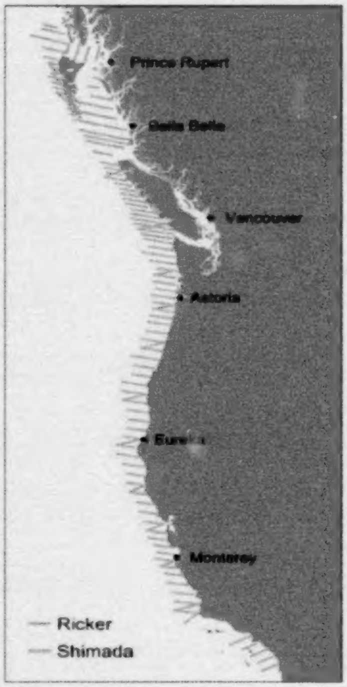

Figure 21-1. Map of the 2015 Pacific Hake survey coverage. Transects in orange were surveyed by the NOAA Bell M. Shimada while transects in blue were surveyed by the CCG W.E. Ricker.

The Pacific Hake fishery is one of the largest fisheries on the west coast of the U.S. and Canada. This requires monitoring and management of the population on both sides of the border. Hake has been managed in Canada since 1992, with Canada joining the U.S. in their hake research program that had previously been in place since 1975. The joint U.S. and Canadian integrated acoustic-trawl survey is the primary fishery-independent tool used to assess the distribution, abundance and biology of the Pacific Hake population. The survey was completed on a triennial basis until 2003, when the decision to switch to a biennial basis was made. In 2004, the U.S. enacted a treaty that detailed an agreement with Canada on the joint management of Pacific Hake. This treaty dictated a joint survey on a triennial basis, however the survey has continued on a biennial (or annual) basis since 2003. The treaty also divides the annual quota between the two countries, giving 73.88% of the quota to the U.S., leaving 26.12% to the Canadian fishery.

The 2015 survey effort included 120 parallel transects that were run from southern California to southern Alaska (Figure 21-1). Transects were 10-20 nmi apart and spanned from the 50 m isobath to the 1500 m isobath along each transect. Transects would extend beyond the 1500 m isobath if there was still obvious hake signal to ensure the offshore extent of the population was properly covered. Acoustic marks were targeted with a midwater trawl to assess species composition, length distribution, and other biological parameters. Backscatter assigned to Pacific Hake was interpolated between transects to obtain an overall estimate of abundance for the entire coast. Using the biological information gained from the midwater trawls, the backscatter was scaled to biomass using the fish length to target strength (TS) relationship (Traynor 1996).

The distribution of hake has been variable over the history of the survey, with the widest distribution seen in 1998 (Figure 21-2). In 2015, the hake distribution was constricted and did not extend as far to the north and south as in previous years, being concentrated between northern Vancouver Island (50° N) and Point Reyes, California (37 ° N). While the range of Pacific Hake was narrower in 2015, the estimated biomass was much higher than in previous years (calculated to be 2.156 million metric tonnes (mmt)). This is the highest biomass estimate in the history of the survey. The next highest biomass in recent record is from 2003, with a biomass estimate of slightly less than 2 mmt (Figure 21-3). For the first time since 2007, age-1 Hake was seen in Canadian waters (Figure 21-4), extending as far north as Barkley Sound. While age-1 Hake is not used in the biomass estimate, it is used in the stock assessment model as an indicator of recruitment.

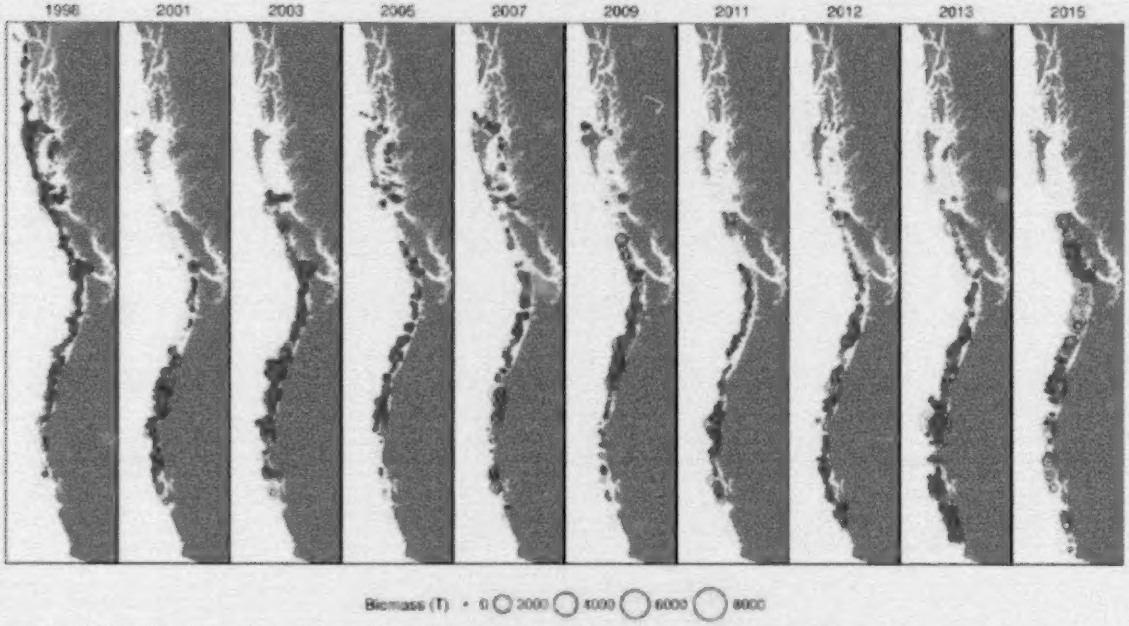

Figure 21-2. Northeast Pacific distribution of Pacific Hake from 1998-present.

Commercial fisheries did not fulfill the quota allotted to them in the beginning of the 2015 fishery. Commercial fleets in the U.S. had trouble finding schools of Hake to target. The biomass in the U.S. seemed to be patchier than previous years; with the fish aggregating in dense schools had a deeper distribution than usual. It also appeared that these aggregations were situated further offshore than the fishers were used to. In Canada, the commercial Hake fleet appeared to abandon their target species part way through the season for species that were selling for a higher price, as the price of Hake was low in 2015.

It has been observed that during warm ocean conditions (such as the 1998 El Niño event) a larger proportion of the stock migrates into Canadian waters, apparently due to intensified northward transport (Agostini et al. 2006). The proportion of Pacific Hake into Canadian waters in 2015 was the largest observed since 2009 (Figure 21-4), but their distribution did not extend much beyond the northern tip of Vancouver Island. These trends and observations emphasize the need for more research into the links between environmental variables and the migration of Pacific Hake.

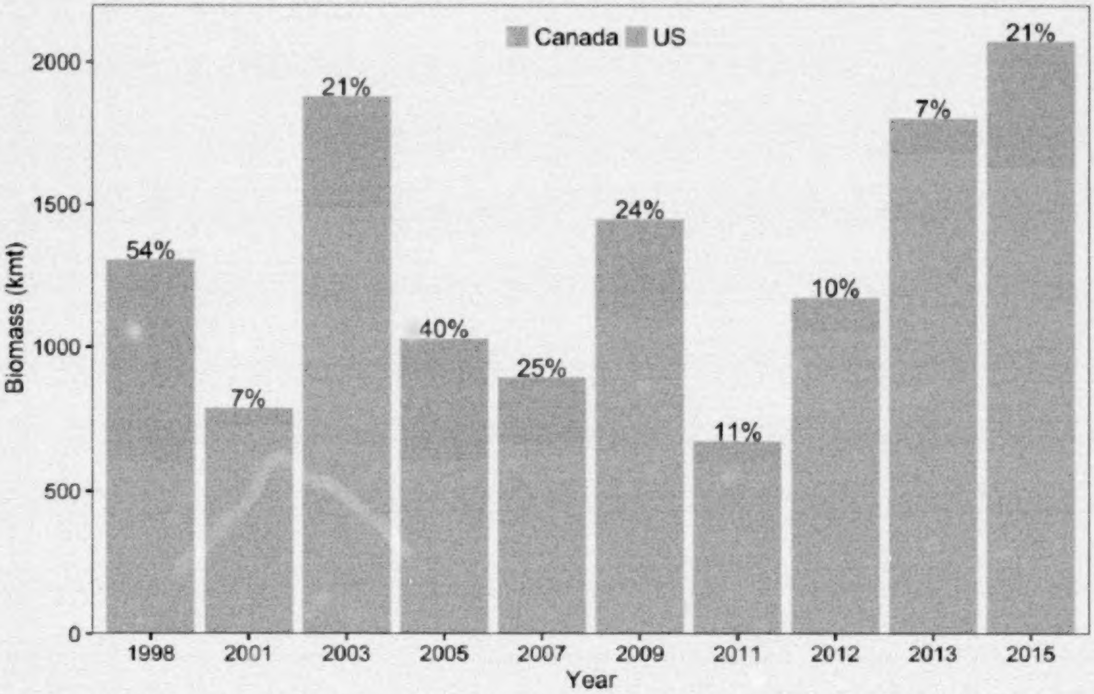

Figure 21-3. Total Hake biomass from 1998-present, showing proportion found in US and Canada.

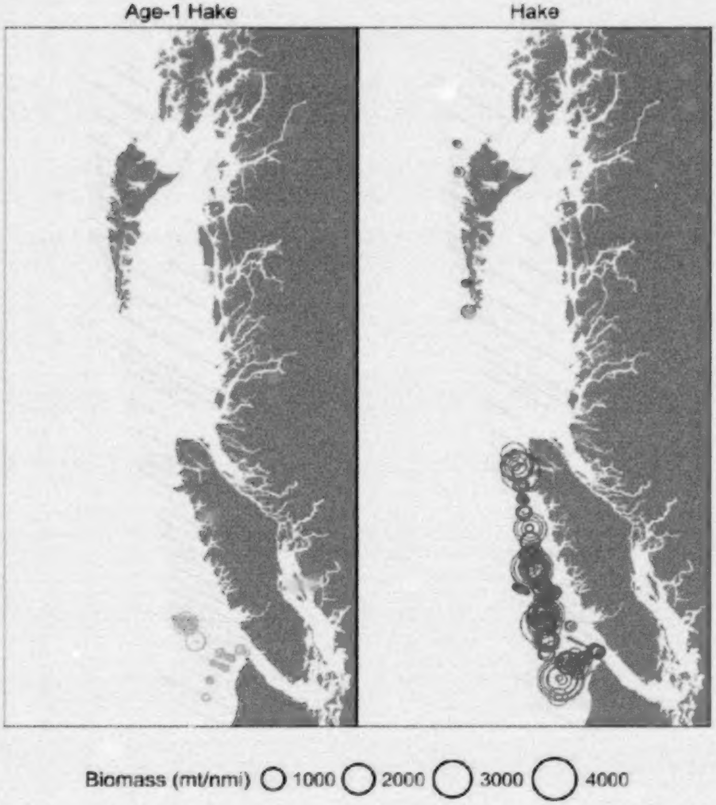

Figure 21-4. Distribution of Age-1 and adult Pacific Hake in Canadian waters in 2015.

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22. SOCKEYE SALMON INDICATOR STOCKS – REGIONAL OVERVIEW OF TRENDS, 2015 RETURNS, AND 2016-2018 OUTLOOK

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22.1. Highlights

- The 2014-15 anomalously warm "Blob" in the North Pacific Ocean did not induce widespread salmon recruitment failures in 2015 due to common ocean effects as some feared but, as anticipated (Hyatt et al. 2014), did influence return timing, straying rates and size-at-age traits of many salmon populations originating from eastern Pacific waters from south-central Alaska, through B.C., Washington and Oregon.
- 2015 returns were above average for many, but not all, salmon stocks (e.g. Okanagan sockeye were far above average and Barkley Sound sockeye achieved a new record return of 2.1 million fish but returns of Fraser Sockeye and Pinks were half of that expected in 2015).
- Impacts of a warmer than average ocean in 2014-2015 followed by an El Niño in spring 2016 suggest survival unfavourable conditions for juvenile salmon making sea entry from the B.C. central to south coast in those years so significant reductions in returns to many populations (Okanagan-Columbia River salmon; Barkley and west coast Vancouver Island salmon) may be expected in 2016-2018.

22.2. Summary

Studies by Mueter et al. (2002a, 2002b) and Pyper et al. (2005) suggest associations between Pacific Salmon survival and coastal environmental variables (upwelling index, sea surface temperature [SST], and sea surface salinity [SSS]) are strongest at local spatial scales (<500 km intervals) for adjacent stocks and exhibit little to no co-variation at scales larger than 1000 km. Correlation scales for SST in summer most closely matched the correlation scales for salmon survival. Regional averages of SST appeared to be better predictors of survival than large-scale measures of SST variability (e.g. the Pacific Decadal Oscillation, Mueter et al. 2002b). Regional-scale variations in coastal SST's may reflect processes causing co-variation in survival rates of neighbouring stocks. Thus, the latter may be expected to exhibit stronger similarities in survival and production variations than widely separated stocks. In addition, geographical overlap of salmon species during freshwater and early marine life stages appear more important in determining shared environmental effects on survival rates than life history differences between species (Pyper et al. 2005).

Comparisons of forecasts and observed returns of Sockeye Salmon for major rivers and fisheries in B.C. have been completed annually by DFO for decades (Figure 22-2). Given the observations above, production trends for major sockeye populations or stock aggregates (i.e. "indicator stocks") may reflect environmental changes and production trends for other salmon species originating from coastal-areas constituting separate production domains. Trend comparisons (1970-2015) among sockeye indicator stocks permit the following generalizations:

- Return variations are large with maximum annual returns at 10-90 times minimum returns.
- Maximum returns for all sockeye indicator stocks from the North Coast to the Fraser occurred in the early 1990s in association with a powerful 1989 La Niña event 2-3 years

earlier. Similarly, a major La Niña in 2008 was followed in 2010/11 by record to near-record returns of sockeye to Vancouver Is. (Barkley), Fraser R. (Chilko), and Columbia R. (Okanagan), reversing a trend for several years of sub-average returns (Figure 22-2).

- As anticipated earlier (Hyatt et al. 2011, 2013a, 2013b, 2014), southern sockeye stocks, with sea-entry into the northern California Current upwelling domain (Okanagan, Barkley sockeye) exhibited rapid rebuilding (2009-2015) to record returns (Okanagan in 2014, Barkley in 2015), i.e. the decadal-scale, geographically-widespread, production-decline of sockeye from southeast Alaska to southern B.C., reported by Peterman and Dorner (2012) has not persisted.
- By contrast, Transboundary (Tahltan, Tatsamenie) and North Coast (Nass, Skeena) stocks continued a decadal-scale, average (Transboundary) to sub-average return trend (Nass, Skeena) through 2015.
- Although there are several examples in each sockeye indicator series for which observed returns diverged greatly from pre-season forecasts (Figure 22-2), the latter commonly anticipate decadal-scale trends within each of their six coastal production domains of origin.
- Returns for most central and north-coast stocks were close to pre-season expectations in 2015, higher than expected for Okanagan and Barkley stocks and 50% lower than expected for Chilko and Fraser stocks.
- SST and/or ENSO indices in the Pacific shifted to strongly positive in 2014-2015 so Columbia River (principally Okanagan) and west coast Vancouver Island sockeye (principally Barkley Sound) salmon marine survivals are likely to decline significantly for these sea-entry years (i.e. 2016-2018 adult return years). Returns of Barkley and Okanagan sockeye are anticipated to decline well below their recent all-year averages in 2016 (panels 5 and 6 in Figure 22-2).
- Observations of exceptionally warm offshore waters in the North Pacific throughout 2014 and of warming of inshore waters by late June were associated with biological signals that reflected an ambiguous mixture of “cold ocean” spring conditions and “warm” ocean summer conditions along British Columbia’s continental shelf (details in Chandler et al. 2015).
- The weight of evidence indicates that salmon survival is determined primarily during the first several weeks after sea entry. Thus, for Sockeye and Chinook Salmon from B.C.’s south coast, conditions for sea entry were ambiguous in 2014 affecting adult returns expected in 2016 and then highly unfavourable in spring 2015 for adult returns beginning in 2017. However, given that 2015 returns of Coho Salmon were lower than average, it now appears that reduced marine survivals and returns are likely for southern Sockeye and Chinook stocks in both 2016 and 2017.
- Marine survivals exhibited by sockeye indicator stocks originating from production domains in the Central, North Coast, and Transboundary areas and returning in 2015 were mixed with no clear indications of strong trends.
- Stock assessment biologists and fisheries managers use in-season observations of abundance-at-age (inferred survival) and abundance-by-week (inferred timing) to develop an informed opinion of whether a given return will follow a pre-season forecast or deviate greatly from it.
- As anticipated in 2014, (Hyatt et al. 2015) deviations from average return timing did materialize in association with anomalously warm ocean conditions through 2014 and 2015. For example, Okanagan sockeye returns to the Columbia River were

approximately 1 week earlier than average while Barkley Sound sockeye returns were later than average which complicated in-season management.

- Anomalously warm ocean temperatures during winter 2014 through summer 2015 were expected to induce unusual biological traits or behaviours for adult salmon returning in 2015 (references in Chandler et al. 2015). Numerous reports from commercial and recreational fisheries sources suggest the occurrence of widespread reductions in size-at-age of adult coho salmon (in Oregon, Washington and B.C. waters) and adult Sockeye Salmon (in commercial fisheries from Bristol Bay Alaska to the Nass and Skeena River fisheries in B.C., e.g. Figure 22-1).
- There was strong evidence of unusual levels of straying by Sockeye Salmon adults from both Okanagan and Barkley Sound stocks into non-natal rivers in 2015 (e.g. hundreds of Somass and Okanagan River origin sockeye adults strayed into distant rivers such as the Puntledge R. and Wenatchee R. respectively) during the July to September return interval.
- Although ocean conditions may have influenced return migration routes, it is likely that straying by Barkley Sound sockeye returning to the Somass River and Columbia River sockeye returning to the Okanagan River were influenced greatly by temperature and to a lesser extent discharge conditions during 2015 in their rivers of origin (Hyatt et al. 2016).

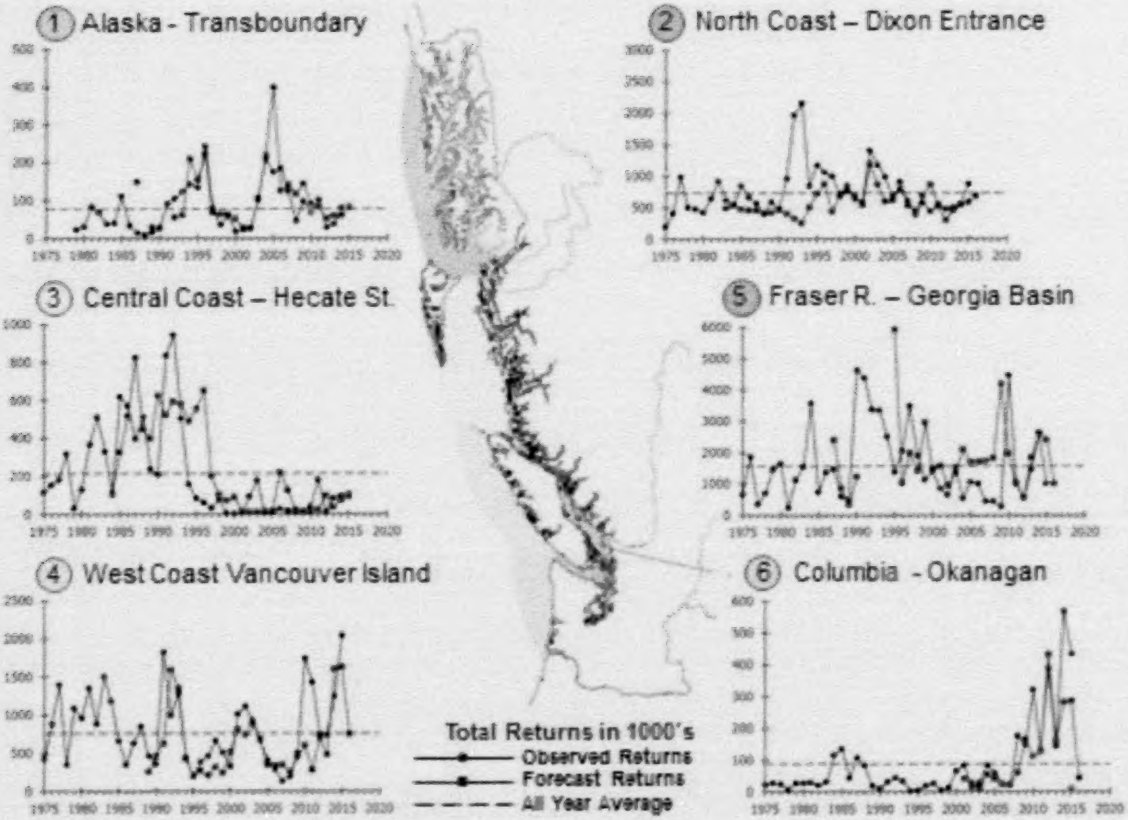

Figure 22-2. Trends in the total returns and forecasts for British Columbia sockeye index stocks including: 1. Tahltan, 2. Nass, 3. Smith's Inlet, 4. Chilko, 5. Barkley Sound, and 6.Okanagan Sockeye Salmon. Y-axis represents returns in thousands of fish. Okanagan 2015 (red point) represents <12000 adults that survived migration to reach the terminal spawning area in the Okanagan River.

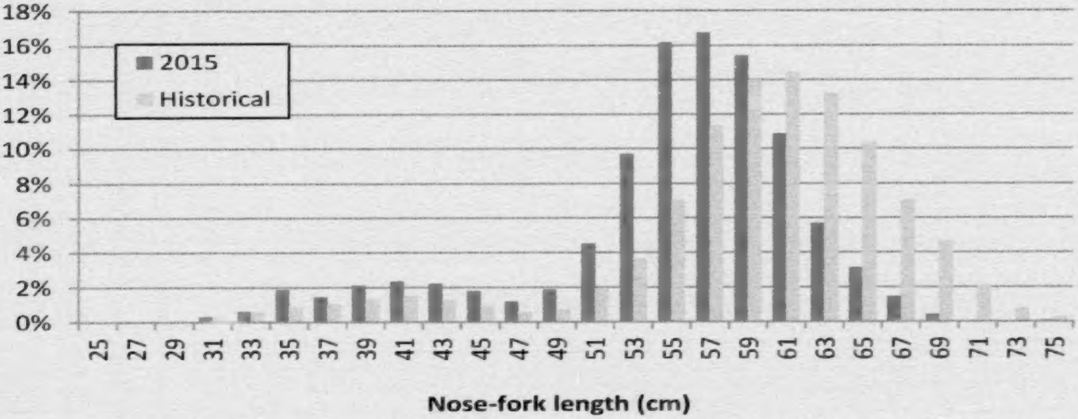

Figure 22-1. Comparisons of sizes of age-four adult Sockeye Salmon returning to the Nass River fish-wheel in 2015 relative to their all-year average size.

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23. TRENDS OF CHINOOK SALMON ABUNDANCE IN FISHERIES MANAGED UNDER THE PACIFIC SALMON TREATY

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23.1. Highlights

- Large abundances for several far north migrating stocks of Chinook Salmon have contributed to a recent, third peak in the relative abundance for five of six major fishing areas under the jurisdiction of the Pacific Salmon Treaty.
- The relative abundance of Chinook Salmon has recently been about double the average abundance during 1979-1982 for the northerly fisheries in southeast Alaska and northern British Columbia, but it was near (i.e. WCVI troll and Central B.C. troll) or below average for other fisheries (e.g. Washington/Oregon Coast troll and Strait of Georgia sport).

23.2. Chinook Model Abundance Indices

Under the jurisdiction of the Pacific Salmon Treaty (PST), 30 Chinook Salmon stock aggregates and 25 fisheries distributed between southeast Alaska and northern Oregon are managed annually to either projected landed catch targets or are limited by maximum allowed exploitation rates. Estimates of escapements or terminal runs of mature fish for each of the stock aggregates and estimates of numbers of Chinook landed or released in the PST fisheries are assembled annually and provide some of the crucial data inputs to the calibration of the Coast-wide Chinook Model (CM). The Chinook stocks (consisting of both wild- and hatchery-origin fish) and fisheries represent nearly all Chinook and fishing-related impacts known to occur within the PST jurisdiction.

A result of the CM calibration procedure is a time series of aggregate Chinook abundance estimates for each fishery starting with 1979 and ending with the most recently completed fishing year. For each stock and fishery, abundances are estimated for up to four age classes, including immature fish that would not spawn for one or more years. An abundance forecast is also generated for the upcoming fishing year and is the basis for establishing the annual catch targets in three highly mixed-stock ocean fishery areas (southeast Alaska [SEAK], Northern B.C. including areas around the Queen Charlotte Islands [NBC], and west coast Vancouver Island [WCVI]).

Time series of abundance indices (AIs) are annually derived and reported to the Pacific Salmon Commission in technical reports prepared by the bilateral Chinook Technical Committee (e.g. PSC 2015, 2016). The AIs are derived by dividing the annual estimated Chinook abundance in any one fishery by the average from the 1979-1982 'base period'. These provide a means to assess temporal and spatial trends in the relative abundance of Chinook stocks contributing to regional fisheries.

The time series of AIs for some of the major northern ocean fisheries (Figure 23-1) show generally that relative abundance has been consistently higher than in southern fisheries (Figure 23-2). More interestingly, Chinook abundance has reached a high of more than twice the base period average (BPA) in the most northerly fishery (SEAK troll) and a low of less than one quarter the BPA in the most southerly fishery (combined Washington [WA] and Oregon [OR] ocean troll).

There have been three obvious peaks in abundance (1988, 2003, and 2014) in the two most northerly fisheries, SEAK troll and NBC troll, with lows just dipping below the BPA (Figure 23-1). In southerly fisheries (e.g., WCVI troll and WA/OR troll), there have been corresponding smaller peaks, with abundances mostly below the BPA (Figure 23-2). Abundances in the 'inside' area fishery, covering all of Georgia Strait and Juan de Fuca sport in B.C., declined below its BPA early in the time series, with abundances of about half the BPA during the last two decades.

The annual calibration of the CM in 2016, supported by agency forecasts for some of the major Chinook stocks, indicated large abundances for several of the far north migrating stocks during 2014-16. These stocks contribute substantially to most northerly fisheries under jurisdiction of the Pacific Salmon Commission (e.g., SEAK troll and NBC troll) and to a lesser degree southerly fisheries (e.g. WCVI troll and WA/OR troll) that encounter the far north migrating stocks while they migrate south to their spawning rivers. Far north migrating stocks originating from the Columbia River, Fraser River, and WCVI have either had large abundances in 2014 or 2015, or they are expected to have a large abundance in 2016. The 2016 CM calibration projects a modest decrease for the southerly fisheries. Several of the fall-run stocks originating from the Fraser River, lower Columbia River, and Puget Sound rivers that reside mainly in the southerly fisheries have been below the BPA for several years, hence the relatively lower abundance compared to northern fisheries.

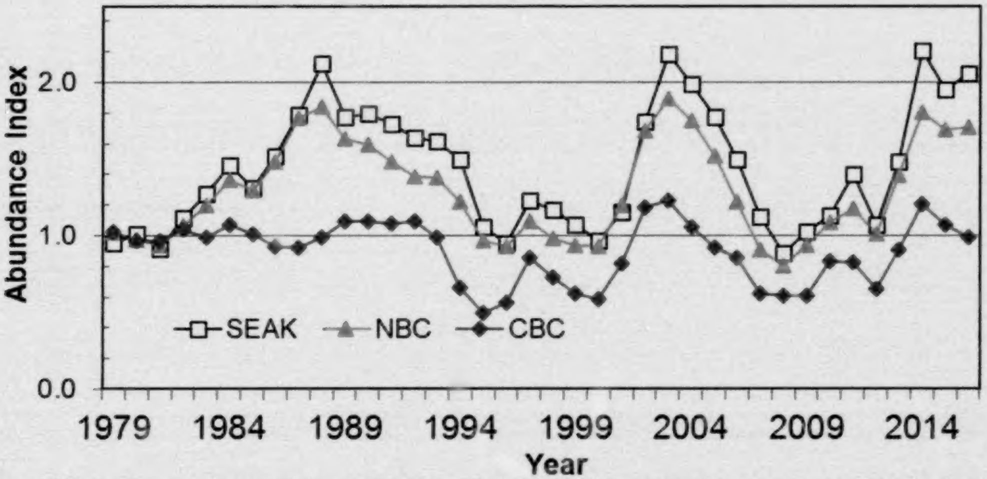

Figure 23-1. Time series of Chinook Salmon abundance indices for three major northerly PST fisheries, 1979-2016. The fisheries are southeast Alaska troll (SEAK), northern B.C. troll in statistical areas 1-5 (NBC) and central B.C. troll in statistical areas 6-12 (CBC). Please note that 2016 values are forecasts resulting from the March 2016 calibration of the Coast-wide Chinook Model.

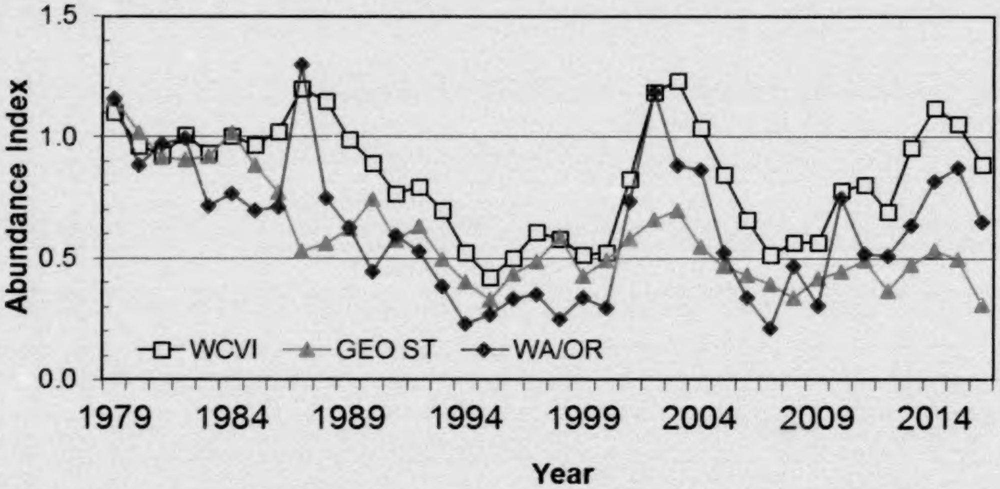

Figure 23-2. Time series of Chinook Salmon abundance indices for three southerly PST fisheries, 1979-2016. The fisheries are West Coast Vancouver Island troll (WCVI), Georgia Strait and Juan de Fuca Sport (GEO ST), and Washington and northern Oregon ocean troll (WA/OR). As in Figure 23-1, the 2016 values are forecasts.

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24. THE SUMMER TRAVELS OF ALBACORE TUNA IN 2014 AND 2015

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24.1. Highlights

- Fishery catch data suggests that albacore availability was above average in 2014 and 2015 owing to increased overlap in time and space between tuna waters (14-19 °C) and feeding areas off of the continental shelf edge where upwelling dominates productivity.
- In 2014, there was an unusually high abundance of Albacore Tuna northwest of Haida Qwaii, whereas the majority of tuna were caught off the west coast of Vancovuer Island in 2015

24.2. Summary

Albacore Tuna (*Thunnus alalunga*) is a highly migratory pelagic species widely distributed in the temperate waters of the North Pacific Ocean from the east coast of Japan to the west coast of North America. Juvenile albacore between the ages of 2 and 4 years migrate seasonally into the coastal waters of North America from mid-June to the end of October. These fish are the primary target of the Canadian fishery, which uses troll gear to target juveniles in the surface waters in the Canadian and United States exclusive economic zones (EEZ) and the adjacent high seas along the west coast of North America and the adjacent high seas waters. All data on this stock are fishery-related since the wide ranging migratory behaviour of albacore is challenging for representative fishery-independent sampling.

Annual variations in the distribution and abundance of juvenile albacore in the coastal waters of North America are related to sea surface temperature and food availability (Alverson 1961; Laurs et al. 1984). Albacore abundance is higher near warm, low chlorophyll oceanic waters, and within 100 km of sea surface temperature (SST) fronts, i.e., steep gradients in temperature (Xu et al. 2015). Juvenile albacore in the eastern Pacific Ocean are most frequently harvested at SSTs between 14 and 19 °C within the transition zone between the subarctic and subtropical gyres. These tuna waters and the albacore within them move north and south seasonally and, on average, arrive in the Canadian exclusive economic zone (200 mile limit) beginning in mid to late July and persist through October. Variations in this timing of these seasonal movements affects the availability of albacore in B.C. waters (Figure 24-1). Juvenile albacore move into B.C. waters to forage on small pelagic fishes (Northern Anchovy, Pacific Sardine, Pacific Saury, Pacific Mackerel, Pacific Hake) and squids (Glaser 2010) over the continental slope and seaward of the edge of the continental shelf.

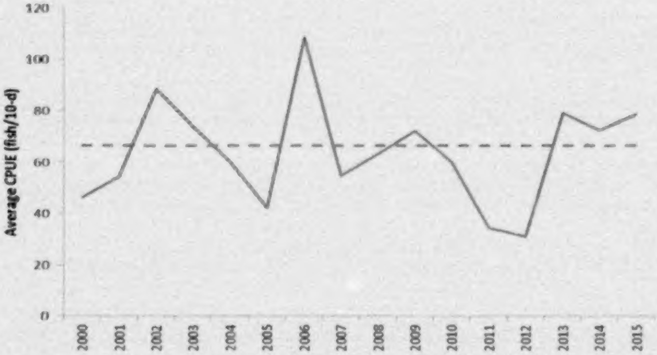

Figure 24-1. Albacore catch rate (fish/10-day) in Canadian waters. The dashed red line is the average catch rate (66 fish/10-d) for the 2000-2009 period.

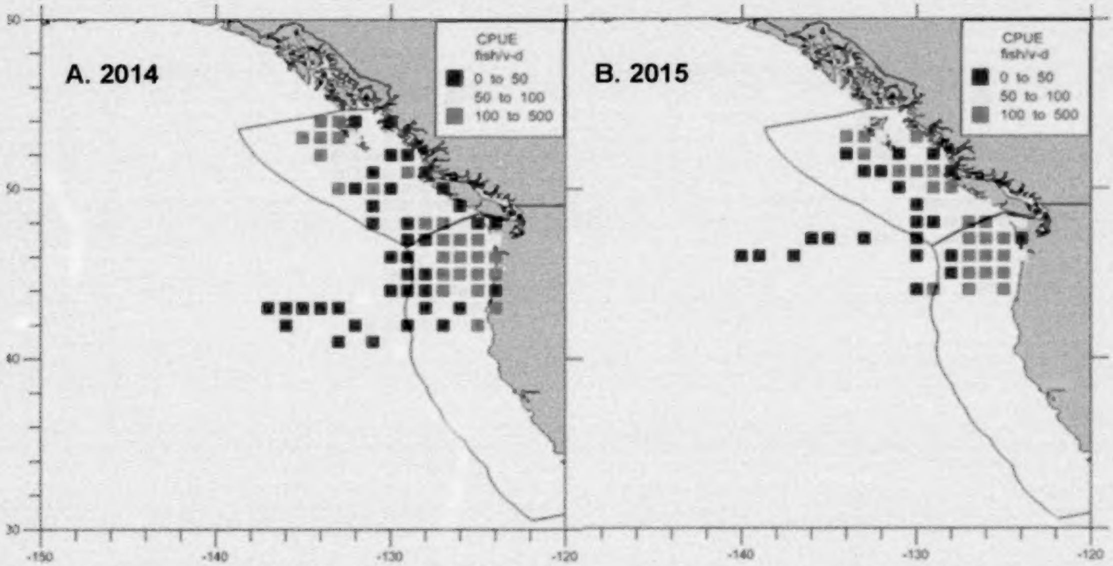

Figure 24-2. Distribution of albacore catch rates (fish/vessel-day) reported by the Canadian fishery in (A) 2014 and (B) 2015. Data are plotted for 1° x 1° spatial blocks. Catch rates are estimated as the total number of fish caught within a block from June through October divided by the total number of vessel-days (effort) in that block during the same period.

Catch-per-unit-effort (CPUE) or catch-rate (total catch divided by the effort to achieve that catch) is often used to index fish abundance. Annual CPUEs for albacore in B.C. coastal waters averaged 66 fish/day during the 2000-2009 period, and the 2014 and 2015 catch rates were above average at 73 and 79 fish/10-day, respectively (Figure 24-1). Albacore catch rates are positively correlated (r = 0.69) with July-Oct upwelling index anomalies at 48°N, 125°W, where positive anomalies indicate higher than average upwelling during the summer and fall and negative anomalies are lower than average upwelling for the same period. Above average upwelling supports higher productivity in lower trophic levels on the continental shelf, which in turn enhances albacore foraging opportunities on small pelagic fish and squids over the continental slope. Stronger upwelling winds blow from the northwest along the Vancouver Island shelf, and not only upwell more nutrient-rich water near shore, but also push this water and its richer marine life over the continental slope, where tuna prefer to feed. This stronger offshore flow of surface waters might also intensify the frontal features offshore of the shelf break, concentrating prey for tuna.

The distribution of albacore in 2014 was substantially different from 2015 and other years. In 2014 anomalously warm oceanic waters were observed pushing inshore throughout the Gulf of Alaska (Crawford 2015). Albacore were observed as far north as the border between British Columbia and Alaska (and there were anecdotal reports of albacore in southeast Alaskan waters), with a catch rate hotspot located at the north end of the Canadian EEZ (Figure 24-2). Although it is not unusual to see hotspots northwest of Haida Gwaii related to 1 or 2 vessels fishing for 1-2 weeks, the 2014 hotspot was based on 30-40 vessels fishing in the area from the beginning of September through to the end of the fishery in early October, reflecting the persistence of unusually high albacore abundance in the area. In contrast, the anomalously warm waters had moved offshore by the 2015 season and while the distribution of albacore was superficially similar to 2014, the majority of albacore were found off the west coast of Vancouver Island, below 52°N. The high catch rates northwest of Haida Gwaii in 2015 were not persistent (2 week period) and were not widespread (only 2-3 vessels).

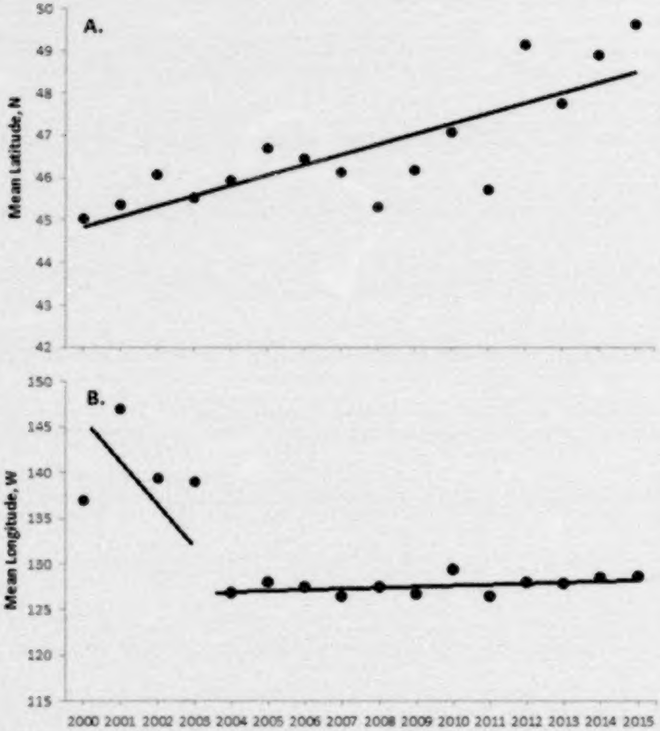

Figure 24-3. Annual means and trends (lines) in latitude (A) and longitude (B) occupied by the Canadian Albacore Tuna fishery from 2000 to 2015.

The Canadian albacore fishery has changed from an offshore fishery operating on the high seas around 150°W early in the 2000s to a coastal fishery operating primarily within the waters of the Canadian and United States EEZs by 2004-05 (Figure 24-3). During the same period, the fishery was also shifting north along the coast from a mean operational latitude in the United States EEZ (<48°N) to a location in 2015 (49.6°N) well within the Canadian EEZ. The change from oceanic to coastal operations in the early 2000s is likely related to high fuel costs and the consistent availability of albacore in coastal waters. In contrast, the northward shift may be related to ocean conditions and treaty-related access to the United States EEZ. Although the number of Canadian vessels permitted in the United States EEZ for fishing was reduced since 2012, the northward movement predates this change in access. Other causes such as albacore distribution responding to a warming of ocean conditions may be important drivers of the northward shift, but have not been fully explored at present.

Tuna waters arrived in the Canadian EEZ earlier than normal in early July and persisted to the end of October in 2014 and 2015. The highest catch rates consistently occurred along the seaward side of the continental shelf in both years as far north as north western Haida Gwaii (Figure 24-2). Total catch of albacore in B.C. waters was 2,645 t (55% of the fishery) in 2014 and 2,9352 t (67% of the fishery) in 2015. This is a 48% increase relative to the catch in 2012 (2,033 t), although effort in B.C. waters in both years was 32% and 10% lower than in 2013. The increase in catch combined with a decline in effort supports the conclusion that albacore availability was above average in 2014 and 2015 owing to increased overlap in time and space between tuna waters (14-19 °C) and feeding areas off of the continental shelf edge where upwelling dominates productivity. Assessments of interannual temporal and spatial variation in albacore distribution and abundance may benefit from considering indices of environmental processes at various spatial scales.

24.3. References

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25. FIN WHALES IN BRITISH COLUMBIA: INSHORE HABITAT USE IN HECATE STRAIT, QUEEN CHARLOTTE SOUND AND THE CONFINED WATERWAYS OF CAAMAÑO AND CAMPANIA SOUNDS

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25.1. Highlights

- Fin Whales are present year-round in Hecate Strait and Queen Charlotte Sound.
- Analysis of Fin whale vocal activity from autonomous acoustic recorders indicates that highest calling activity occurred during the months of November to January in Hecate Strait coinciding with the breeding season for this species in the North Pacific.
- Mark-recapture modelling of individual photo-identifications produced an estimate of 328 animals (95% CI: 230-426) in 2014 in the region of Hecate Strait and Queen Charlotte Sound.
- Presence of Fin Whales in Caamaño Sound, a relatively confined waterway on the northern B.C. coast adjoining Hecate Strait, appears to be associated with foraging and represents a re-occupation by these whales of historically important habitat.

25.2. Summary

Fin Whales are listed as Threatened under SARA. Like many large whale species in the North Pacific, Fin Whale populations were severely depleted by commercial whaling in the North Pacific, >40,000 kills from approximately 1908 through the 1970s. In British Columbia alone, coastal whaling stations killed 7,605 in the years 1908 to 1967. Fin Whales have since been considered relatively a uncommon species in B.C. waters although they have been the third most frequently sighted species during ship based surveys since 2002 (Ford et al. 2010).

The inshore waters of Hecate Strait, Queen Charlotte Sound, and the confined waterways of Caamaño and Campania Sound are the focus of this report (Figure 25-1). This summary presents the key findings of a recent analysis of data from multiple field studies to assess habitat use, seasonal occurrence and behaviour of Fin Whales in Hecate Strait, Queen Charlotte Sound and Caamaño and Campania Sounds. The multiple studies and analyses include:

- Sightings and effort data from ship-based surveys used to investigate and model Fin Whale distribution;
- Photo-identification of individual animals used to investigate movements, site fidelity and to estimate abundance using mark-recapture methods;
- Satellite-linked telemetry data from tagged individuals used to investigate behaviour including diving behaviour and movements of whales;
- Acoustic monitoring data used to investigate seasonal occurrence and behaviour of fin whales.

Observations from dedicated ship-based surveys that have transected Hecate Strait, Queen Charlotte Sound and Dixon Entrance during annual surveys (2002-2014) and acoustic data from autonomous recorders that were deployed for up to a year during the period 2009 to 2015, together demonstrate that Fin Whales are present year-round in Hecate Strait and Queen Charlotte Sound. This finding is consistent with observations noted by Mizroch et al. (2009) of a diffuse migratory pattern and year-round occurrence in high latitudes in the North Pacific.

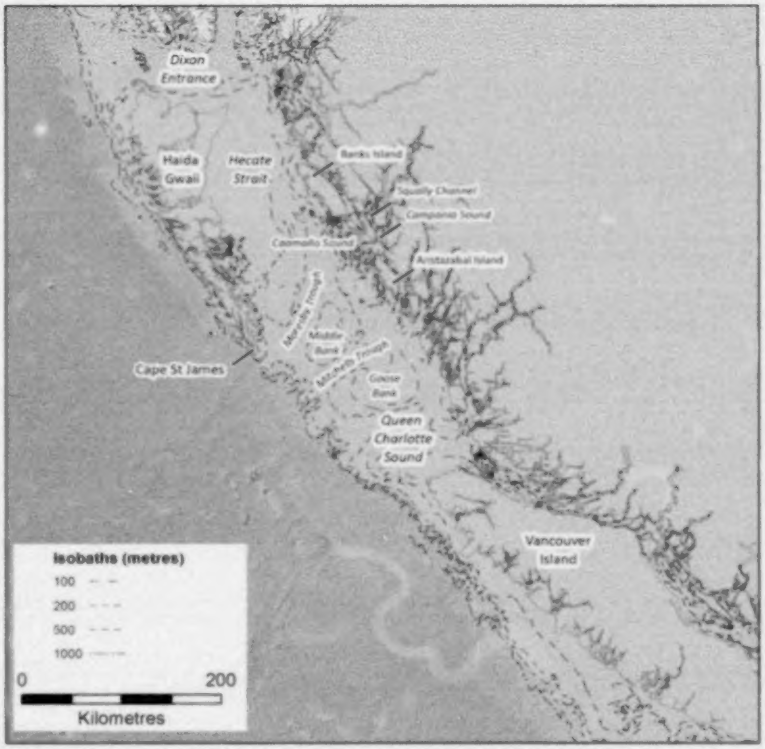

Dixon Entrance
Haida Gwaii
Hecate Strait
Banks Island
Squally Channel
Campania Sound
Caamaño Sound
Aristazabal Island
Moresby Trough
Middle Bank
Mitchell's Trough
Cape St James
Goose Bank
Queen Charlotte Sound
Vancouver Island
Isobaths (metres)
100
200
500
1000
0
200
Kilometres

Figure 25-1. Pacific coast of Canada showing Hecate Strait, Queen Charlotte Sound and Caamaño and Campania Sounds and other place names mentioned in the text.

Modeling of sightings from ship surveys (2002-2014) in Hecate Strait and Queen Charlotte Sound as a function of depth, slope and geographic coordinates revealed an association between Fin Whales and Moresby Trough, a deep-water gully that extends northeast from the shelf break south of Haida Gwaii. It also showed an association between Fin whales and the heads of submarine canyons near the 1000 m depth contour between Cape Scott and Cape St James, and with areas along the mainland coast, particularly Caamaño Sound (Figure 25-1). The predicted distributions agreed well with the predictions of Fin Whale distribution in the region by Best et al. (2015).

A mark-recapture abundance estimate using photo-identifications of 283 uniquely marked whales photo-captured over a six-year sampling period in the region (2009-2015) yielded an estimate of 328 animals (95% CI: 230-426) in 2014 in Hecate Strait and Queen Charlotte Sound and Caamaño and Campania Sounds. This estimate is consistent with abundance estimates made using line transect survey data in the region (Best et al. 2015).

Historical catch records from the B.C. whaling era indicate that in a 15-year period (1952-66), 240 Fin Whales were killed in Hecate Strait and Queen Charlotte Sound, of which 47 were killed in Caamaño Sound. Fin Whales were also hunted in Hecate Strait and Queen Charlotte Sound in the earlier years of B.C. coastal whaling, beginning as early as 1910 (Nichol et al. 2002), but catch locations were not consistently reported making it impossible to determine the total take in this area in the years 1910 to 1951.

Fin Whales produce a distinctive 22 Hz vocalization. These calls are produced by males and are associated with breeding behaviour. Fin Whale calls were detected on autonomous acoustic recorders throughout the fall and winter in B.C. Acoustic monitoring sites in Hecate Strait and Queen Charlotte Sound had the greatest and most sustained calling activity of all sites analysed

(Figure 25-2). Calling activity peaked during November to January which coincides with the breeding season reported for this species in the North Pacific (Mizroch et al. 2009), suggesting that breeding may occur in Hecate Strait and Queen Charlotte Sound. Data from Fin Whales killed during the whaling era in B.C. revealed that 75% of females were pregnant and would have calved between mid-October and mid-February, suggesting that Fin Whales may also be calving in B.C. waters

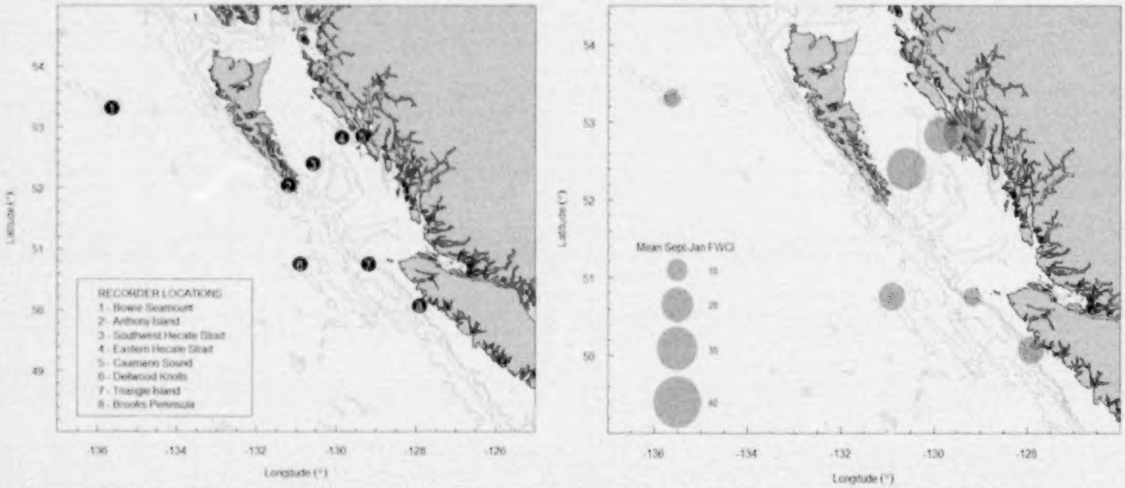
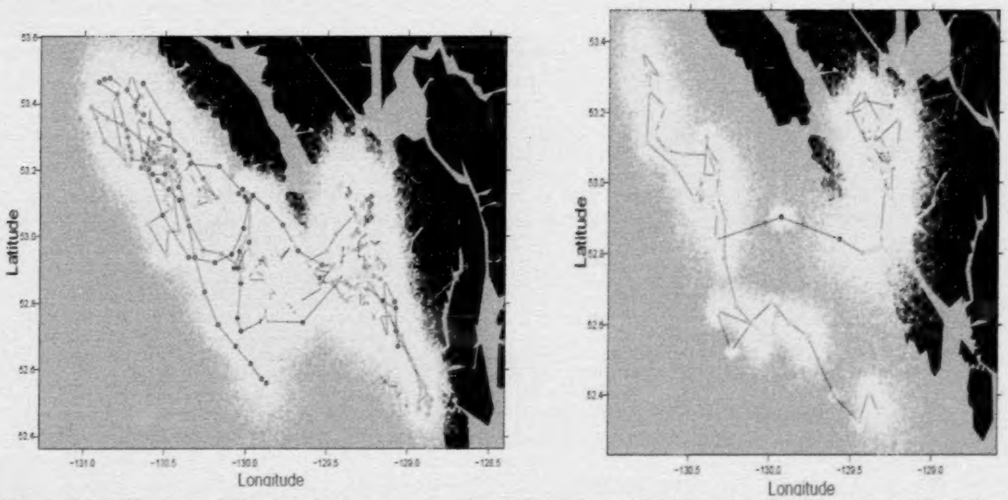

54
53
52
51
50
49
Latitude (°)
1
2
3
4
5
6
7
8
RECORDER LOCATIONS
1 - Bowie Seamount
2 - Anthony Island
3 - Southwest Hecate Strait
4 - Eastern Hecate Strait
5 - Caamano Sound
6 - Dellwood Knolls
7 - Triangle Island
8 - Brooks Peninsula
-136
-134
-132
-130
-128
-126
Longitude (°)
54
53
52
51
50
Latitude (°)
Mean Sept-Jan FWCI
10
20
30
40
-136
-134
-132
-130
-128
Longitude (°)

Figure 25-2. Left panel: locations of 8 autonomous acoustic recorder deployment sites, Right panel: greatest amount of sustained calling was in Hecate Strait with peak calling November to January. Size of represents relative amount of calling activity

We tagged Fin Whales with satellite-linked telemetry tags in Caamaño Sound and Hecate Strait (2011 to 2014). Analysis of the movements of the tagged Fin Whales indicates that animals engaged in Area Restrict Search (ARS) behaviour which suggests foraging activity and then undertook directional movements to new locations within the inshore region (Figure 25-3). Tagged Fin Whales travelled back and forth across Hecate Strait, particularly following the long axis of Moresby Trough. Areas where ARS was recorded included Caamaño Sound, an area west of Banks Island along the 200 m depth contour delineating the northward extension of Moresby Trough, within Moresby Trough at the southwest end near Moresby Island, and also along the mainland side of Hecate Strait. Analysis of satellite–linked tags that also recorded diving behaviour (depth and duration) demonstrated that Fin Whale in Caamaño Sound when engaged in ARS behaviour exhibited consistently deeper dives during the day than at night. This suggests they were foraging during the day on diel vertically migrating zooplankton which would occur in dense patches at depth during the day (Figure 25-4).

25.3. Significance of Trend

Fin Whales, like other large baleen whale species, are major consumers of oceanic productivity and recovering populations will likely contribute to changes in oceanic ecosystems that may become more apparent in Canadian Pacific waters as recovery continues (Croll et al. 2006).


53.6
53.4
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53.0
52.8
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52.4
Latitude
-131.0
-130.5
-130.0
-129.5
-129.0
-128.5
Longitude
53.4
53.2
53.0
52.8
52.6
52.4
Latitude
-130.5
-130.0
-129.5
-129.0
Longitude

Figure 25-3. Selected Fin whale tracks showing locations and inferred behavioural modes (blue represents transiting and yellow represents Area-Restricted-Search (ARS) derived from the hierarchical Bayesian switching state-space model.

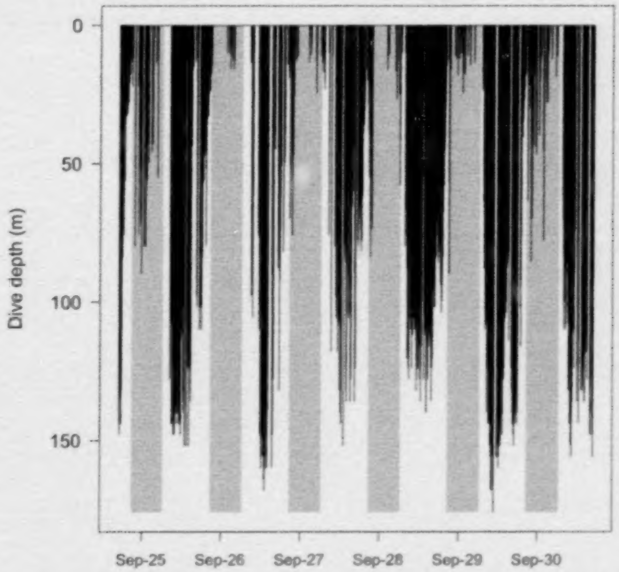

Figure 25-4. Time-depth profile showing maximum dive depths of one Fin Whale over a portion of a dive tag deployment from September 25-30, 2014 (Pacific Daylight Time, PDT). Grey shaded bands indicate periods of darkness bounded by nautical dusk and dawn (period during which the sun drops ≥12° below the horizon.

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26. OBSERVATIONS ON SEABIRDS ALONG THE OUTER COAST

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26.1. Highlights

- Cassin's Auklets had a mediocre breeding season in 2015 on the world's largest colony at Triangle Island, with nestling growth rates in that year close to average compared to the years from 1996 to 2014.
- Research currently underway has identified a warm-water, southerly zooplankton community off the U.S. Pacific coast in fall and winter 2014-2015 as a potential key contributing factor in the mass mortality event that affected Cassin's Auklets through that period.
- There was considerably less juvenile salmon in diets fed to nestling Rhinoceros Auklets on Pine Island in 2015 than in the preceding three years, but the amount fed to nestlings at Lucy Island was normal.

26.2. Growth rates of Cassin's Auklet nestlings

Like other breeding parameters, growth rates of Cassin's Auklet (*Ptychoramphus aleuticus*) nestlings are very strongly affected by oceanographic conditions, which have a profound influence on seasonal patterns of prey availability. In general, nestling auklets grow more quickly on Triangle Island, the world's largest breeding colony, in cold-water years when the subarctic copepod *Neocalanus cristatus* persists in their diets through the bulk of the provisioning period from May to July (Hipfner 2008). Since 2007, growth rates (gauged by 25 day masses) have tended to be above average on Triangle Island, with the notable exception of 2010. Growth rates in the 2015 season were only slightly below long-term averages, which is far better than had been anticipated based on the extremely warm ocean conditions (Figure 26-1).

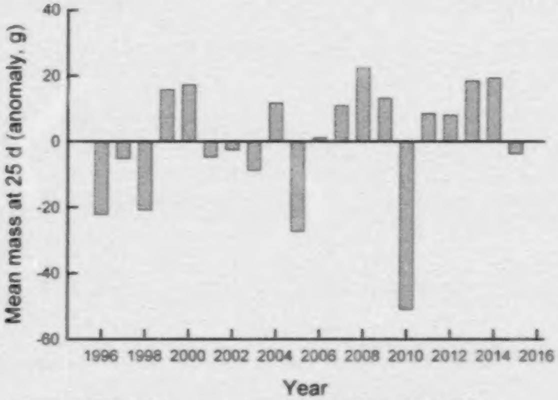

Figure 26-1. Yearly anomalies of mean 25 day mass (a proxy for growth rate) of nestling Cassin's Auklets on Triangle Island, B.C. in 1996-2015.

A massive, coast-wide (California to B.C.) mortality event befell Cassin's Auklets in fall and winter 2014-2015. Similar events, although of smaller magnitude, have occurred in previous years, notably in 1997-1998, and in 2005. Preliminary results based on rates of deposition of beach-cast birds have identified a warm-water, southerly zooplankton community off the U.S. Pacific coast in fall and winter 2014-2015 as a potential key contributing factor.

26.3. Salmon in Rhinoceros Auklet diets

Pacific Salmon (*Oncorhynchus* spp.) have an anadromous life-cycle, spending a few months to 2 years in freshwater, followed by 1-4 years at sea where they fall prey to a variety of fish, mammals and birds. Mortality rates during the marine phase of the life cycle of Pacific Salmon generally exceed 90%, and it is widely believed that most mortality is due to predation in the first few weeks to months following ocean entry (Beamish & Mankhen 2001). On their northerly seaward migration, the vast majority of Pink Salmon (*O. gorbuscha*), Chum Salmon (*O. keta*) and Sockeye Salmon (*O. nerka*) smolts from stocks in southern and central British Columbia funnel past aggregations of hundreds of thousands of Rhinoceros Auklets (*Cerorhinca monocerata*) breeding on colonies scattered along the province's Central and North coasts. The auklets are wing-propelled, pursuit-diving seabirds that forage mainly in the top 5-10 m of the water column and within ~90 km of their breeding colonies. The smolts' migration occurs in June and July, coinciding with the period when the auklets are delivering whole and intact fish, including salmon smolts, to their nestlings.

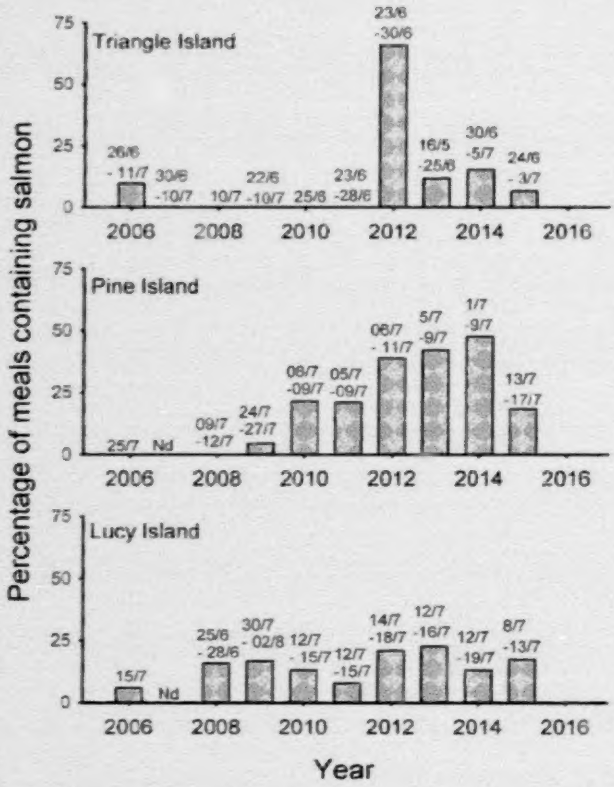

Figure 26-2. Percentage of meals delivered to nestling Rhinoceros Auklets that included one or more salmon (Pink, Chum, or Sockeye) on 3 colonies in B.C., Triangle, Pine and Lucy Islands, in 2006-2015. Dates of sampling (day/month) are indicated above the bars.

Scientists with Environment Canada and the Department of Fisheries and Oceans have been quantifying predation by Rhinoceros Auklets on salmon smolts since 2006, and some clear patterns have emerged (Tucker et al. 2016). First, there is marked temporal and spatial variation in the importance, and species and stock composition, of salmon in nestling diets. In general, salmon is most important at Pine Island; in 2015, however, salmon was present in considerably fewer meals at that site than was the case in 2012-2014 (Figure 26-2). Salmon has been less important, and less variable, in diets at Lucy Island, and the amount present in 2015 was close to average. Salmon was an important component of auklet nestling diets at Triangle Island only in 2012 (almost entirely Fraser River Sockeye), and was a typically rare diet item in 2015.

26.4. References

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Tucker, S., Hipfner, J.M., and Trudel, M. 2016. Size and condition-dependent predation: a seabird disproportionately targets substandard individual juvenile salmon. Ecology 97: 461-471.

Individual reports on conditions in inside waters (including the Strait of Georgia)

27. OCEAN STATE CHANGES AND VARIATIONS IN ENVIRONMENTAL CONDITIONS AFFECTING SOCKEYE SALMON IN THE TERMINAL MARINE AREA OF ALBERNI INLET IN 2015

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27.1. Highlights

- Somass River water temperature is a limiting factor for Sockeye migration in freshwater. In 2015, multiple migration delays occurred in response to elevated river temperatures (>19-20 °C) from mid-June to late August. Delayed migrants pooled in 'holding zones' in upper Alberni Inlet.
- Temperature and oxygen conditions in the holding zone at the head of the inlet appear to be related to PDO/ENSO state, with high surface temperatures and low oxygen concentrations (i.e. poorest water quality for Sockeye) coincident with warm phase PDO and El Niño conditions in 2015.
- Holding Sockeye prefer temperatures of 9-12 °C and oxygen concentrations greater than 4 ppm, but will select 9-12 °C water, even if oxygen concentrations are sub-optimal (O_2 <4 ppm). In 2015, a significant proportion (>10%) of Sockeye holding in Alberni Inlet suffered prolonged exposure to oxygen concentrations below 4 ppm.

27.2. River Temperature Conditions Affecting Migrating Sockeye

Alberni Inlet is a narrow inlet on the west side of Vancouver Island, stretching from Barkley Sound about 40 km inland where it meets the outlet of the Somass River at Port Alberni. The Somass River drains two major Sockeye lakes: Great Central Lake via the 25 km Stamp River; and Sproat Lake via the 3 km Sproat River.

Adult Sockeye generally return from the high seas to Barkley Sound from June to mid-September. Returns typically peak in mid-July and, on average, the runs are 75% complete by the middle of August (Hyatt et al. 2015). However, there is considerable annual variation in upstream migration timing depending on environmental conditions, which, in some years have been severe enough to induce mass mortality events of fish prior to spawning. The conditions that lead to mass fish mortality are primarily associated with high freshwater temperatures that prohibit or delay safe migration up the Somass River, combined with prolonged exposure (>30 days) to high temperatures and low oxygen while holding at the head-end of Alberni Inlet.[1]

In stressful years, Somass water temperatures approach 18 °C by early June, and remain above the critical 20 °C threshold associated with migration delays for up to 4-6 weeks. Low discharge levels may exacerbate temperature impacts. The freshwater migration pattern is then characterized by multiple timing gaps and delays (Figure 27-1), and high incidence of mortality, as occurred in 1990, 2004, and 2015 (annual observations of >1,000 pre-spawn mortalities).

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[1] e.g., 48-d delay in 1990; 40-d delay in 2004 (Birtwell et al. 2014; Stucchi et al. 1990)

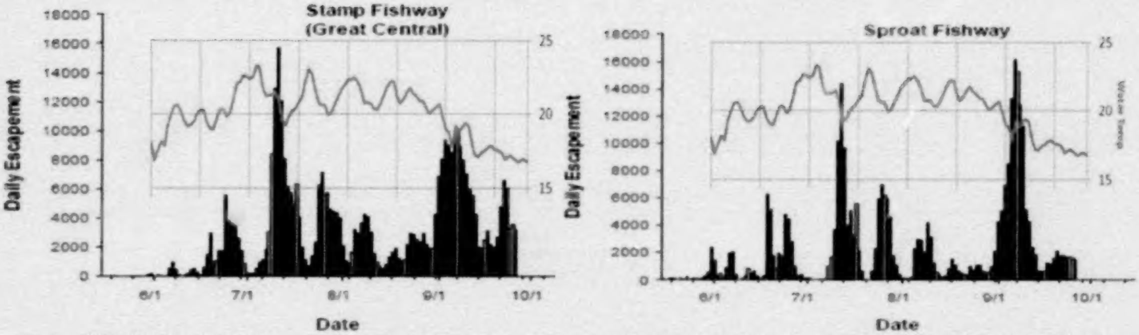

Figure 27-1. Daily Sockeye migrants (black bars) versus Somass water temperature (red line) in 2015.

27.3. Upper Alberni Inlet Temperature-Oxygen Conditions and Ocean State

Upon first holding in the inlet, most adult Sockeye are surface-oriented where they experience seasonal temperatures between 15-20 °C and $O_2 > 6$ ppm. However, given prolonged delays (>1-2 weeks) they will choose to hold in deeper, cooler (9-12 °C) waters where O_2 levels vary seasonally and inter-annually, and range from adequate ($O_2 > 4$ ppm) to poor ($O_2 < 3$ ppm).

Given these observations, DFO Science Branch personnel (Hyatt and Stiff, unpublished results) have developed temperature and oxygen indicators based on (a) Sockeye distribution and holding behaviour in the inlet; (b) water quality depth profiles[2]; and (c) previous year-outcomes (i.e. safe passage versus elevated mortalities) that define the weekly volume of safe water that exists for Sockeye holding in the area seaward of Polly Point in Alberni Inlet (Figure 27-2):

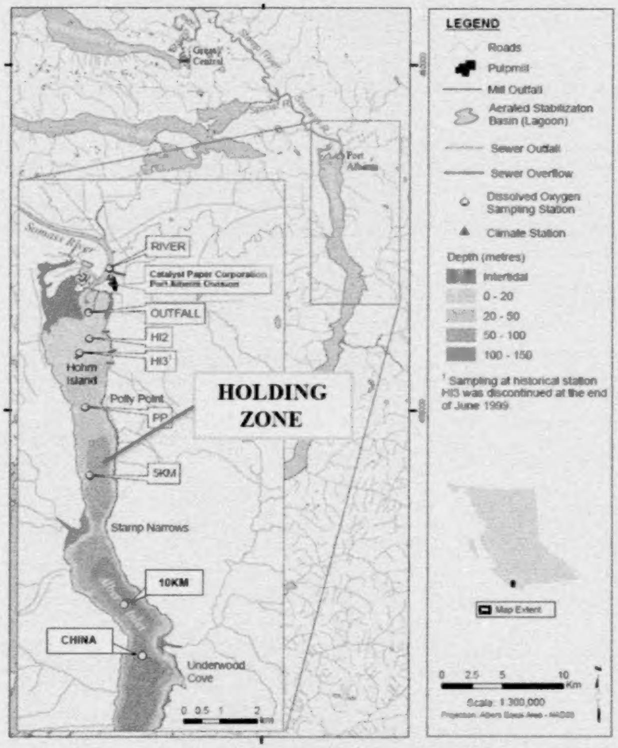
LEGEND
Roads
Pulpmill
Mill Outfall
Aerated Stabilization Basin (Lagoon)
Sewer Outfall
Sewer Overflow
Dissolved Oxygen Sampling Station
Climate Station
Depth (metres)
Intertidal
0 - 20
20 - 50
50 - 100
100 - 150
¹ Sampling at historical station HI3 was discontinued at the end of June 1999
Map Extent
Scale 1:300,000
Great Central
Port Alberni
Somass River
RIVER
Catalyst Paper Corporation Port Alberni Division
OUTFALL
HI2
HI3¹
Hohm Island
Polly Point
PP
HOLDING ZONE
5KM
Stamp Narrows
10KM
CHINA
Underwood Cove

Figure 27-2. Upper Alberni Inlet temperature-oxygen profile sites sampled by Catalyst Paper Corporation as part of Environment Canada's Pulp and Paper Environmental Effluent Monitoring Program. Map adapted from Hatfield Consultants (2012).

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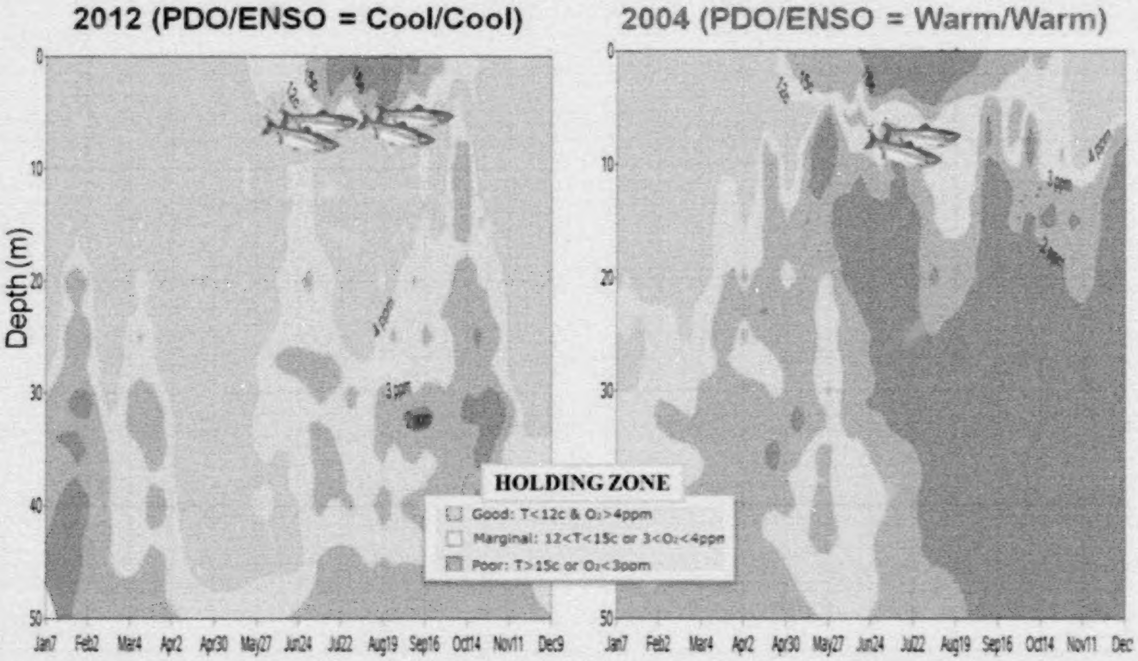
[2] Temperature and oxygen depth profile data (1990-2015) courtesy of Catalyst Paper Corporation, ENVIRONMENTAL EFFLUENT MONITORING PROGRAM.

- Good conditions: $T < 12°C$; $O_2 > 4$ ppm
- Marginal conditions: $12°C < T < 15°C$; $3 < O_2 < 4$ ppm
- Poor conditions: $T > 15°C$; $O_2 < 3$ ppm

Application of these thresholds permits classification of inter-annual and seasonal changes in environmental conditions, from excellent (e.g. 2012: no migration delays, little mortality) to poor (e.g. 2004: long delays, significant mortality) (Figure 27-3).


2012 (PDO/ENSO = Cool/Cool)

2004 (PDO/ENSO = Warm/Warm)

Figure 27-3. Weekly temperature-oxygen conditions at depth in holding zone between Polly Point and Stamp Narrows, Alberni Inlet, in 2012 (left) and 2004 (right).

Review of historical data[3] revealed an unexpected temperature-oxygen versus depth pattern in the upper inlet holding area: during 'cool phase' PDO and ENSO conditions (e.g. 2012), Sockeye encounter acceptable conditions for holding ($T < 12$ °C, $O_2 > 4$ ppm), but during "warm phase" PDO and ENSO conditions (e.g. 2004) there is virtually no acceptable water for Sockeye to hold in at the head end of the inlet (Figure 27-4).

Under such conditions, where Sockeye must choose between well-oxygenated but hyperthermic surface waters versus hypoxic but cooler depths, hydroacoustic surveys indicate that the fish will congregate at the cooler temperatures, even though oxygen conditions are sub-optimal.

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[3] IOS/CTD Database: 1941, 1957-1988; EEM Program: 1990-2015

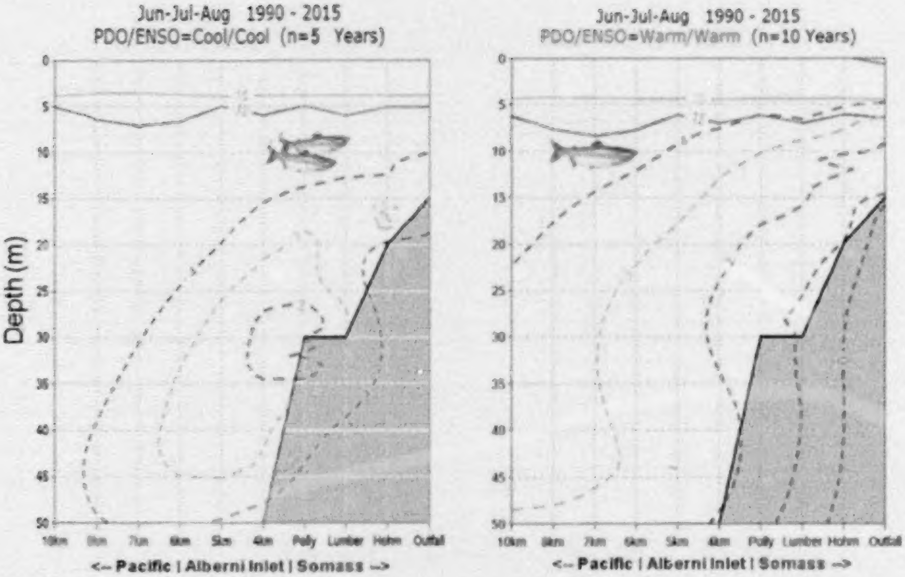


Figure 27-4. Cross-sectional profile of upper Alberni Inlet, by PDO/ENSO ocean state. Typical temperature-oxygen conditions at depth in "cool" (left), and "warm" (right) phases of PDO/ENSO ocean state.

27.4. Alberni Inlet Temp-Oxy Conditions Affecting Holding Sockeye in 2015

Alberni Inlet environmental conditions in spring 2015 developed within the context of a warm-phase PDO and the onset of a moderate to strong El Niño event (i.e., warm-warm conditions). This represented the first co-occurrence since 2004 of both a warm-phase PDO and El Niño. Thus, the expectation as of June 2015 was that environmental conditions would be very similar to other warm years, such as 1990 and 2004.

Onset of marginal to poor conditions in the Holding Zone emerged by early June to confirm our initial expectation and persisted through to early September (Figure 27-5, left). As the season progressed:

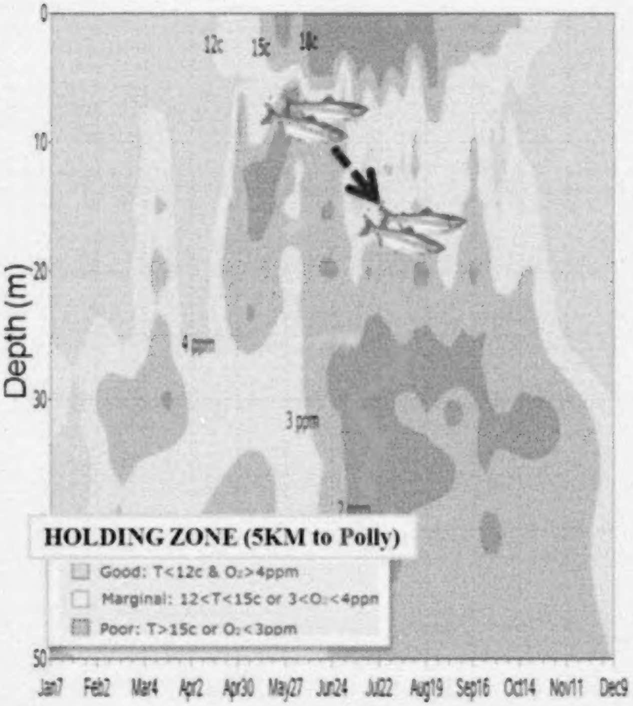
(1) Sockeye exhibited 4-5 prolonged migration delays in the Somass River due to elevated water temperatures;

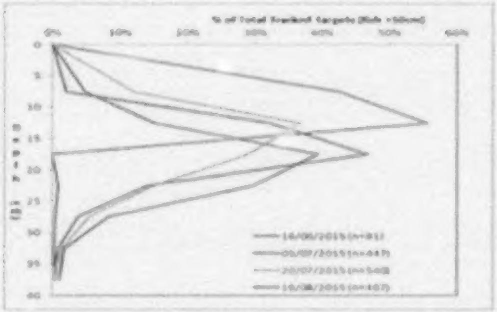
(2) During delays, Sockeye first pooled in Alberni Inlet at 5-10 m depths, and then sought deeper waters (<12 °C) at 15-25 m (Figure 27-5, right);

(3) Sockeye were exposed to sub-optimal oxygen levels when holding inside of Stamp Narrows for prolonged intervals.

Alberni Inlet water quality surveys were extended by DFO in 2015 to Uchucklesit Inlet. Results indicated that suitable environmental conditions for extended holding by Sockeye were continuous seaward of Stamp Narrows, though restricted to mid-depth locations. Hydroacoustic surveys detected few targets in the marginal holding zone between Stamp Narrows and Polly Point in June, but this rose to 10% by mid-August as the numbers of holding fish increased.

Acoustic- and trawl-based lake surveys of juvenile Sockeye production will be conducted during the summer and fall of 2016 to determine whether fry recruitment success may have been influenced by migration delays and sub-optimal holding conditions for adult Sockeye in Alberni Inlet in 2015.





Depth	16-Jun	09-Jul	20-Jul	18-Aug
0	0%	0%	0%	0%
5-10	43%	2%	12%	5%
10-15	56%	32%	37%	15%
15-20	0%	47%	29%	39%
20-25	1%	14%	15%	30%
25-30	0%	4%	5%	8%
30-35	0%	1%	1%	2%
35-40	0%	0%	0%	1%
N	81	447	540	467

Figure 27-5. Temporal depth profile of upper Alberni Inlet, 2015 (left). Hydroacoustic surveys of fish in the Holding Zone indicated Sockeye moved to cooler depths as the season progressed.

27.5. References

Birtwell, I.K., Wright, M.E., and Edgell, P. 2014. Aquatic habitat in the Somass River estuary: a selective review and implications to Chinook salmon. Prepared for Fisheries and Oceans Canada, Nanaimo; Alberni Valley Enhancement Association, B.C. DFO CATNO 352934. 151p.

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28. HAKAI OCEANOGRAPHY PROGRAM: CENTRAL COAST AND NORTHERN STRAIT OF GEORGIA TIME SERIES

Brian P. V. Hunt[1,2], Jennifer M. Jackson[1], Alex A. Hare[1], Kang Wang[1,2]

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[2]Earth Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, B.C.

28.1. Highlights

- Average conservative temperature in the upper 50 m of the water column from Pruth station on the Central Coast was approximately 2 °C warmer during the winter of 2014/2015 than the winter of 2013/2014.
- Low winter nutrient renewal was associated with a reduction in 2015 phytoplankton biomass on the Central Coast to half the levels of 2013 and 2014. Spring bloom timing was approximately 15 April.
- Average conservative temperature in the upper 100 m of the water column from stations QU24/QU39 in the northern Strait of Georgia was approximately 1 °C warmer in the fall of 2015 than the fall of 2014.
- Spring bloom timing in the northern Strait of Georgia was approximately 15 February in 2015, one month earlier than the peak of the bloom in the southern strait.

28.2. Summary

The Hakai Oceanography Program (HOP) is an integrated multidisciplinary program founded on the principals of Long Term Ecological Research. The HOP maintains year-round, long-term measurement of key physical, chemical and biological (microbes, phytoplankton, and zooplankton) parameters underpinning coastal marine ecosystems. Details of the HOP sampling can be found on the Hakai Institute webpage (www.hakai.org/). Currently, the HOP maintains two full time observatories, one on Calvert Island on the Central Coast (operated since June 2012), and the other on Quadra Island, which operates in the northern Strait of Georgia and Discovery Islands (since November 2014).

28.2.1. Central Coast

The HOP Central Coast observatory routinely samples a suite of stations extending from Rivers Inlet in the south to the McMullin Islands in the north, and spanning the inner to the outer coast. (Figure 28-1). Core stations, defined by routine full parameter measurement, are located in Queen Charlotte Sound (QCS01), Kwakshua Channel (Pruth), Fitz Hugh Sound (FZH01), and Rivers Inlet (DFO2). Pruth station is sampled on a daily basis between early spring and fall, and all other stations are sampled every 2-3 weeks during this period. Winter sampling frequency is every 6 weeks and is reduced to stations that are in close proximity to Calvert Island.

The Calvert Island Pruth station has the longest CTD time series and we focus on physical data from this station for the purpose of this report. Average conservative temperature in the upper 50 m of the water column was approximately 2 °C warmer during the winter of 2014/2015 than the winter of 2013/2014 (Figure 28-2). Data from a suite of B.C. time series indicate that ocean conditions were anomalously warm at the decadal scale (Chandler 2015, Crawford 2015, Dewey et al. 2015), and resulted from the onshore advection of a warm water mass (the "Blob") that developed in the NE Pacific in the fall of 2013 (Freeland 2015). The timing of the arrival of this warm water mass on the Central Coast was heralded by the annual maximum temperatures recorded at Pruth on 14 October 2014. Average temperatures remained high through the spring of 2015. Notably, the lob waters were comparatively fresh, and reduced salinity conditions persisted in the upper 50 m until early summer 2015.

The phytoplankton bloom initiation date on the Central Coast was approximately 15 April in 2015, similar timing to 2014 (Figure 28-3). Maximum phytoplankton biomass levels in 2015 (~ 7.5 µg L^{-1}) were approximately half that of 2014 and 2013 (~ 15 µg L^{-1}), and remained low for the duration of the summer season. Size fractionated chlorophyll data showed that the reduction in phytoplankton biomass was attributed to a decline in the contribution of the microphytoplankton size class (> 20 µm), representative of diatoms. Low biomass levels corresponded with reduced winter nutrient renewal in the photic zone in the Central Coast survey region in 2015.

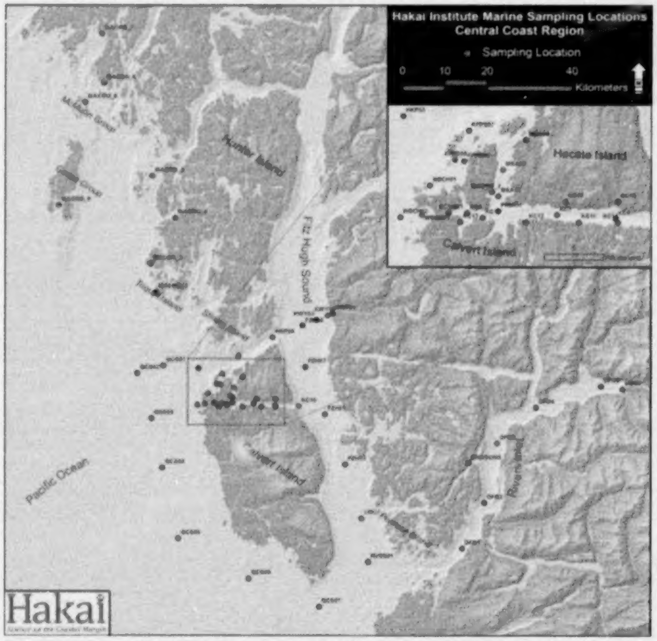
Hakai Institute Marine Sampling Locations
Central Coast Region
Sampling Location
0 10 20 40
Kilometers
Hecate Island
Calvert Island
Hunter Island
Fitz Hugh Sound
Pacific Ocean
Calvert Island
Hakai

Figure 28-1. Hakai Oceanography Program Central Coast stations.

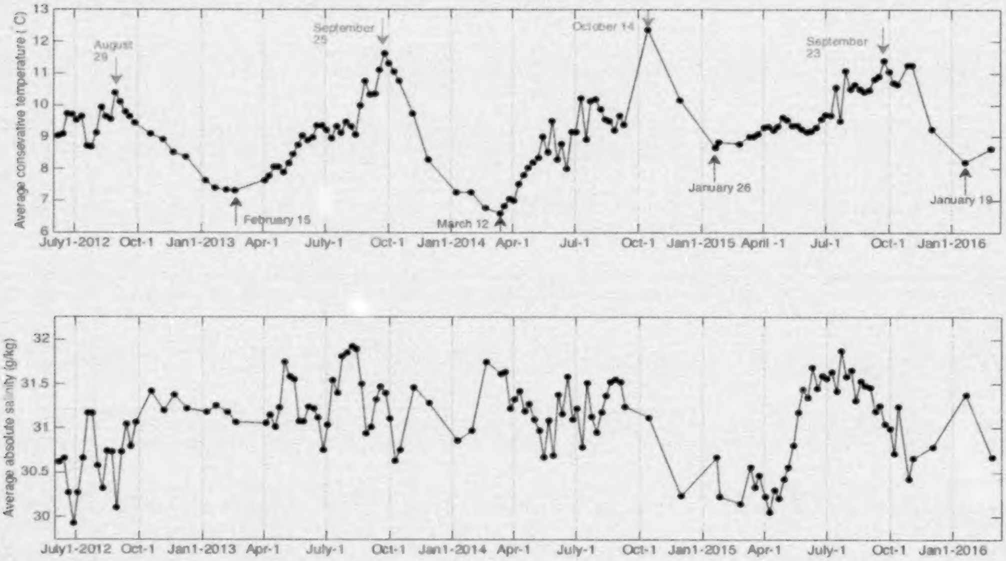

Figure 28-2. Average conservative temperature and absolute salinity from weekly CTD profiles for the upper 50 m at Pruth station on the Central Coast.

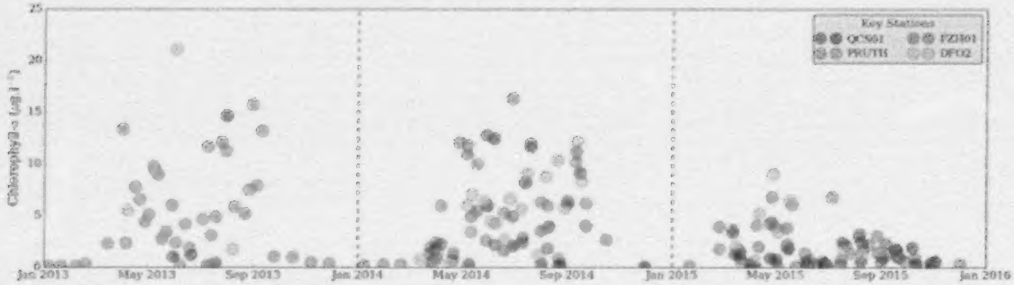

Figure 28-3. Phytoplankton biomass (µg chlorophyll a L^{-1}) at 5 m depth from four core Central Coast stations.

28.2.2. Northern Strait of Georgia & Discovery Islands

The stations sampled by the HOP Quadra observatory are indicated in Figure 28-4. Core stations are located in the northern Strait of Georgia (QU24/39), Hyacinthe Bay (QU5), Sutil Chanel (QU35), Calm Channel (QU33), and Okisollo Channel (QU29). Sampling is weekly at QU24/39, and every 2-4 weeks at other stations. These stations span regions typified by summer stratification, typical of the Strait of Georgia, to regions of high tidal mixing (e.g. Okisollo Channel).

Average conservative temperature in the upper 100 m at QU24/ QU39 shows a seasonal cycle of maximum temperature in late summer/ early fall and minimum temperature in January (Figure 28-5). Absolute salinity was highest in the fall of both 2014 and 2015 and freshest in the winter of 2014-2015. The absence of a decrease in salinity during spring suggests that the spring freshet did not influence this part of the northern Strait of Georgia. The average temperature in the upper 100 m was about 1 °C warmer in the fall of 2015 than the fall of 2014. Whether this difference was associated with typical interannual variability or a delayed response to the Blob has yet to be determined.

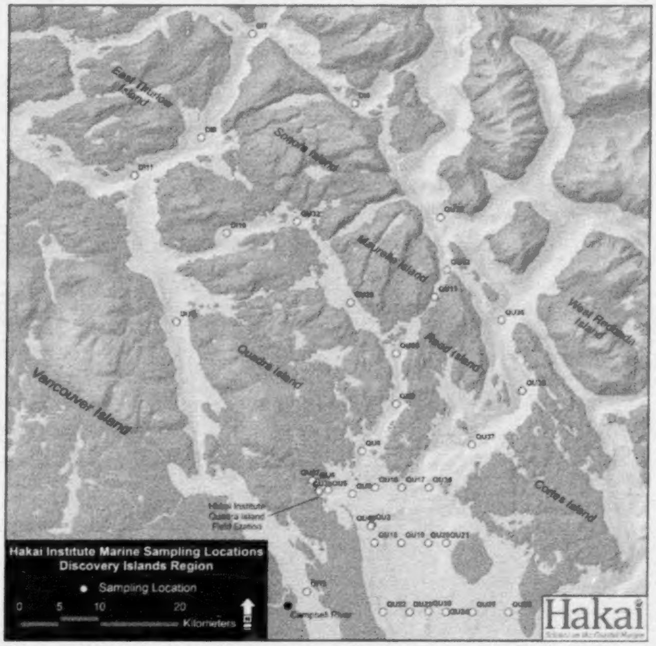
East Thurlow Island
Sonora Island
Maurelle Island
Read Island
West Redonda Island
Quadra Island
Vancouver Island
Cortes Island
Hakai Institute Quadra Island Field Station
Campbell River
Hakai Institute Marine Sampling Locations
Discovery Islands Region
Sampling Location
0
5
10
20
Kilometers
Hakai

Figure 28-4. Hakai Oceanography Program northern Strait of Georgia and Discovery Islands.

The phytoplankton bloom in the northern Strait of Georgia (station QU24/39) commenced in mid-February in conjunction with the onset of surface warming (Figure 28-6). This was one month earlier than the observed peak bloom date in the southern Strait of Georgia (Allen & Latornell 2015). Phytoplankton biomass in the northern Strait of Georgia bloom peaked at ~ 23 µg.L^{-1}. This bloom persisted for approximately one month before tapering off to background levels of ~ 1 µg.L^{-1}. A second, lower intensity bloom developed at QU24/39 in the first week of April. In Sutil, Calm, and Okisollo channels, bloom onset appeared to be delayed compared to the northern Strait of Georgia, first being recorded in late April, and reaching half the biomass levels of the first Strait of Georgia bloom.

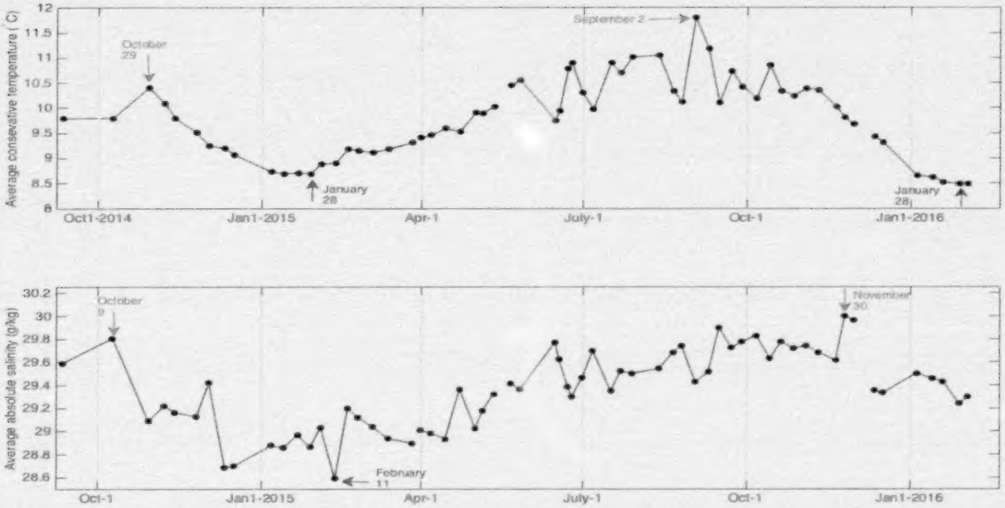

Figure 28-5. Average conservative temperature and absolute salinity from weekly CTD profiles for the upper 100 m at QU24/ QU39 in the northern Strait of Georgia.

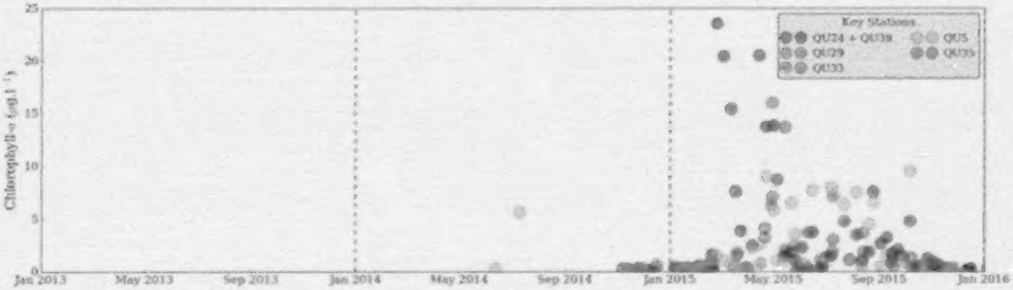

Figure 28-6. Phytoplankton biomass (µg chlorophyll a L^{-1}) at 5 m depth from four core northern Strait of Georgia and Discovery Islands stations.

28.3. References

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29. VANCOUVER AQUARIUM DATA ON SHALLOW SEABED PHYSICAL OCEANOGRAPHY

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29.1. Highlights

- Changes in temperature-pH and temperature-salinity relationships appear to be driven primarily by shallow surface waters during an El Niño.
- No upwelling was detectable on the Howe Sound side of the reef during El Niño.
- Local tidal patterns drive incidences of water temperature increase during the summer.

29.2. Summary

Seabed monitoring by the Vancouver Aquarium's Howe Sound Research dive team now includes continuous monitoring of seawater conditions using two sonde buoys measuring pH, temperature-conductivity (salinity), dissolved oxygen and turbidity at paired locations. During 2015 the first summer and winter of simultaneous data collection was conducted for two sites located 74 m apart on either side of a barrier reef between Howe Sound and Strait of Georgia at 16 m depth. In contrast to results presented in 2015 for these same sites (Marliave et al. 2015), no upwelling on the Howe Sound side occurred during the winter of 2015/16. Notably, this winter's data occurred during a strong El Niño while the previous winter did not qualify as an El Niño under current ONI standards.

The pH range was much greater during summer than winter with summer reaching notably higher pH (summer_{max} = 8.26; winter_{max} = 7.85). Moore-Maley et al. (2016) identified the same seasonal pattern for the upper 20 m of the Strait of Georgia. We found a strong relationship between pH and temperature for both seasons, however summer pH was positively correlated with temperature, while winter pH was negatively correlated with temperature (Figure 29-1). This pattern was consistent between the two sites. A similar reversal of the relationship was seen with salinity and temperature, indicating seasonal differences appear to be driven by shallow surface water (0-3 m) conditions.

A comparison of the Howe Sound reef location over non-consecutive winters shows that temperatures were on average warmer during the 2015/16 winter than the 2013/14 winter (Figure 29-3). During the first comparable week of deployment, December 13 to 20, temperatures in 2015/16 were 1.5 °C warmer than in 2013/14 (9.1 °C vs 7.6 °C). Only during the latter two weeks of January were temperatures warmer in 2013/14 than 2015/16. The coldest temperature reached in 2013/14 was 6.3 °C on February 7, compared to 7.2 °C on January 21 in 2015/16 (daily average temperatures).

Individual temperature data loggers were deployed across Howe Sound in 2015 at depths ranging from 5.8 m to over 21 m. A summer temperature time series (June – September) highlights the influence of large tidal exchanges over the range of depths (Figure 29-2). Each peak in the cycle is linked to week-long daily tidal ranges of greater than 3 m. Of particular note is the late August peak in temperature influenced by a combination of large tidal range and a strong windstorm. Interestingly, this tidal pattern ceases during the winter, even when tidal range is large in late December and January (data not shown). Wind driven events have been shown to increase mixing-layer depths (Moore-Maley et al. 2016) resulting in warm surface waters during summer reaching depths of 21 m.

Strong seasonal patterns of surface water mixing are evident here for a variety of seabed depths approximately 20 m and shallower. This is particularly true during summer extreme tides where wind events likely play an important role in mixing shallow, high-pH surface waters to depths of at least 16 m. Moore-Maley et al. (2016) have shown that these seasonal pH patterns are linked with aragonite saturation cycles that are of direct consequence to calcifying organisms. Inter-annual evaluation of this pattern will be key for understanding ongoing changes to ocean acidity and warming in Howe Sound.

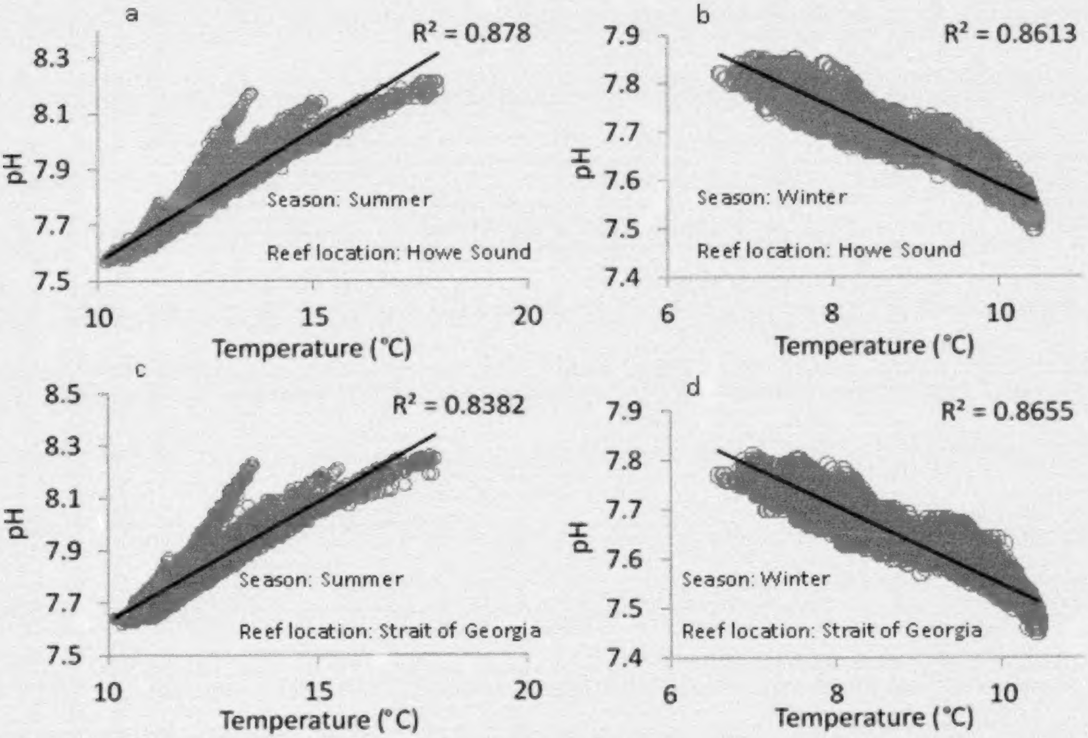

Figure 29-1. The relationship between pH and temperature in summer and winter 2015 for the Howe Sound side (a,b) and the Strait of Georgia side (c,d) of a breakwater reef at 16 m depth.

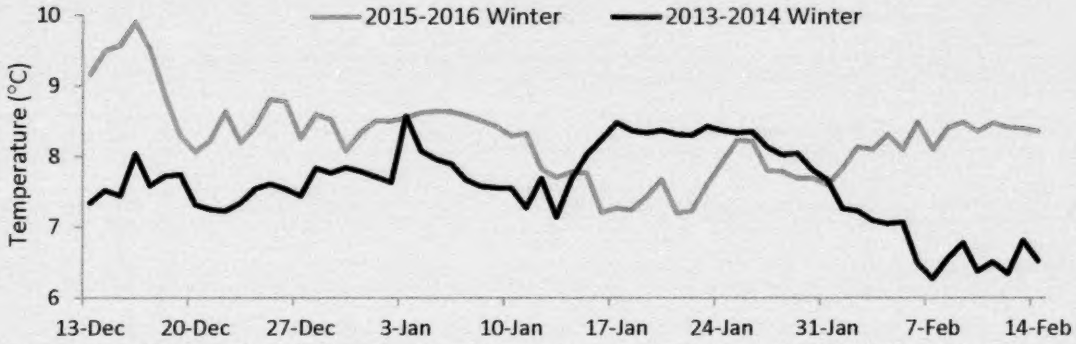

Figure 29-3. Temperature time series for a shallow (16 m) reef during winter 2013/14 and winter 2015/16 in Howe Sound, British Columbia.

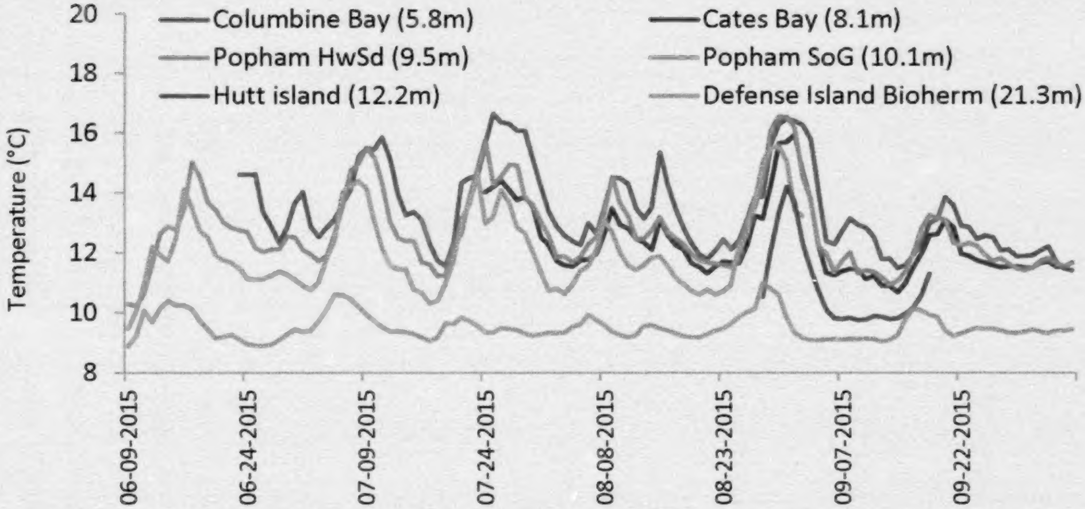

Figure 29-2. Temperature time series for six reefs in Howe Sound, British Columbia for summer 2015 (June – September) at depths ranging from 5.8 m to 21.3 m.

29.3. References

Marliave, J.B., Borden, L.A., Young, S., and Schultz, J.A. 2015. Vancouver Aquarium Data on Ocean Acidification. pp. 195-199 in Chandler, P.C., King, S.A., and Perry, R.I. (Eds.). 2015. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2014. Can. Tech. Rep. Fish. Aquat. Sci. 3131: vi + 211 p.

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30. A NOVEL CARBONATE SYSTEM TIME SERIES FROM A HIGHLY RESOLVED SITE IN THE NORTHERN SALISH SEA

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[2]Vancouver Island University, Centre for Shellfish Research, Nanaimo, B.C., Helen.Gurney-Smith@viu.ca

30.1. Highlights

- Seasonal and shorter time scale variability in carbonate system parameters was revealed by high-speed analyses made near continuously throughout 2015.
- The anthropogenic CO_2 burden for 2015 was estimated to be 64.7 µmol kg^{-1}.
- This burden has driven declines in pH_T and Ω_{arag} of 0.16 and 0.64, respectively.

30.2. Time Series and Anthropogenic CO_2

The invasion of anthropogenic carbon dioxide (CO_2) into the ocean is shifting the marine carbonate system globally such that both seawater pH and the saturation state of calcium carbonate minerals are declining with potentially negative implications for marine ecosystems (Doney et al. 2009, Feely et al. 2004, Orr et al. 2005). In coastal settings, these secular changes in carbonate parameters, collectively known as ocean acidification, are occurring in conjunction with large and often unresolved variability in the marine carbonate system (Harris et al. 2013, Sutton et al. 2016). The northern portion of the Salish Sea, an inland sea enclosed by Vancouver Island and the Olympic Peninsula on the Pacific coast of North America, is one region where carbonate system measurements have been limited and existing data are largely unable to resolve variability across a wide range of temporal and spatial scales.

Beginning in December 2014, a project supported largely by the Tula Foundation using sensors on loan from the Ocean Acidification Research Center at the University of Alaska Fairbanks was initiated with the aim to: (1) assess the variability in surface seawater carbonate chemistry at a well-equipped coastal site, and (2) develop an understanding of the response of economically important shellfish species to the observed *in situ* variability. The location of this site was the Hakai Institute's Quarda Island Field Station (QIFS) located in Hyacinthe Bay. Only the carbonate system measurements and related calculations from Evans et al. (in preparation) are presented in this contribution.

QIFS contains a flow-through laboratory where surface seawater is drawn from a 1 m depth approximately 20 m from shore. A Sunburst Sensors Shipboard Underway pCO_2 Environmental Recorder ($SuperCO_2$) and a Sea-Bird Electronics SBE 45 MicroTSG Thermosalinograph were plumbed into the seawater line within the laboratory. Measurements from these sensors were captured by a control computer every 2 s, which then, following calibration and processing steps, were bin averaged to 5-min data. The processing steps for data handling and quality control are described in Evans et al. (2015) and Evans et al. (in preparation).

The time series of sea surface temperature, salinity, and CO_2 partial pressure (pCO_2) are shown in Figure 30-1. Temperature at the QIFS site ranged from 6 °C in winter to 21 °C in summer. Average salinity (reported here using PSS-78) was 26.3, lower than the adjacent Strait of Georgia (Masson 2006) and with abrupt decreases in salinity to levels as low as 21 during freshets from the local Hyacinthe Creek. pCO_2 levels during winter months (December – February) consistently ranged from 500 to 700 µatm. The spring phytoplankton bloom that occurred in late February drove a rapid transition in pCO_2 from 550 µatm to near 130 µatm in 4 days. Following this transition, surface seawater pCO_2 was generally undersaturated with respect to the atmosphere except during periodic wind mixing events. One particular wind event in June drove a 700 µatm change in pCO_2 over the course of a week. Surface water pCO_2 transitioned back to persistently higher levels during the autumn months.

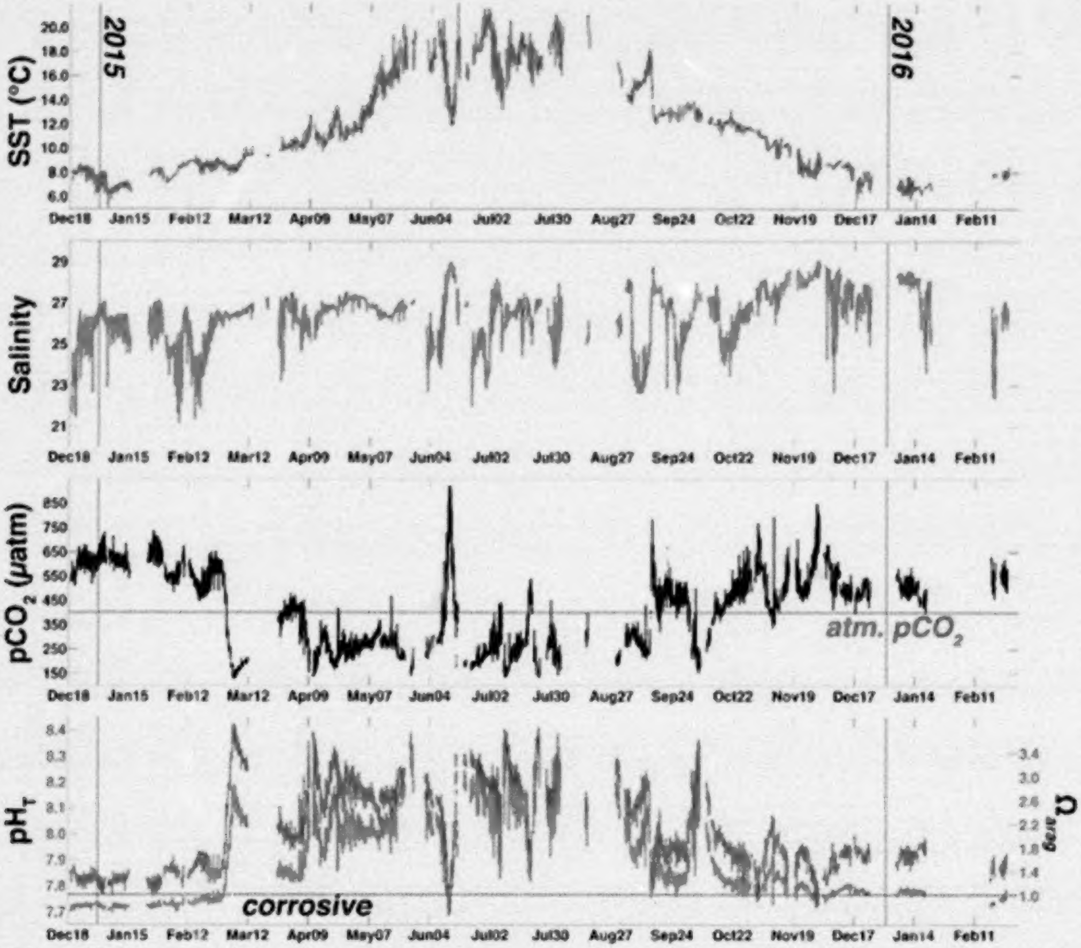

Figure 30-1. The top three panels are sea surface temperature (SST; °C), salinity, and CO_2 partial pressure (pCO_2; µatm) from December 18, 2014 to February 25, 2016. The bottom panel is calculated pH_T (blue) and aragonite saturation state (red; Ω_{arag}) for the same time period. pH_T and Ω_{arag} were calculated using a regional alkalinity-salinity relationship produced from the data reported by Murray et al. (2015). The solid red horizontal line in the pCO_2 panel represents the atmospheric level for 2015; the dashed black horizontal line in the pH_T/ Ω_{arag} panel represents the Ω_{arag} = 1 below which aragonite will have the tendency to dissolve. Data shown are 5-min averages of 2-sec data.

Using the temperature, salinity and pCO_2 data with total alkalinity estimated by a regionally specific alkalinity-salinity relationship built from measurements collected at the Friday Harbor Laboratory (Murray et al. 2015), we calculated pH_T (Total scale) and the saturation state of aragonite (Ω_{arag}; lower panel of Figure 30-1). Winter pH_T and Ω_{arag} levels were near 7.8 and 0.9, respectively. Ω_{arag} levels less than 1 indicate the tendency for aragonite to dissolve. Similar to the pCO_2 dynamics discussed above, the spring phytoplankton bloom drove a large increase in both pH_T and Ω_{arag} to 8.4 and 2.8, respectively. pH_T and Ω_{arag} near this level persisted until autumn except during periodic wind mixing events; lowest pH_T and Ω_{arag} in the time series occurred during the June event mentioned previously. During autumn, pH_T and Ω_{arag} transitioned back to lower wintertime levels.

Using this dataset, an estimate of the anthropogenic CO_2 signal and its influence on Ω_{arag} variability can be computed. Following methods detailed elsewhere (Evans et al. 2015, Feely et al. 2008, Harris et al. 2013, Sutton et al. 2016), the 2015 total inorganic carbon (TCO_2) record was converted to pre-industrial (*circa* 1750) TCO_2 assuming a pre-industrial atmospheric pCO_2 of 280 µatm. A pre-industrial Ω_{arag} record was then calculated using the converted pre-industrial TCO_2 with the 2015 temperature, salinity and derived alkalinity. Histograms of the 2015 and pre-industrial Ω_{arag} records reveal the change in the pattern of variability associated with the uptake of anthropogenic CO_2 (Figure 30-2). Pre-industrial Ω_{arag} extended to much higher levels than in 2015. In addition, peaks in the frequency of observations were shifted toward lower Ω_{arag} values in 2015. The difference between the means of the 2015 and the pre-industrial TCO_2 data records provides a measure of the anthropogenic CO_2 burden that has accumulated up to 2015. This amount was 64.7 µmol kg^{-1}, and was responsible for average decreases of 0.16 and 0.64 units in pH_T and Ω_{arag}, respectively. These changes are large in comparison to global patterns of decreasing pH_T and Ω_{arag} (Feely et al. 2009), and suggest strong sensitivity in the northern Salish Sea to ocean acidification.

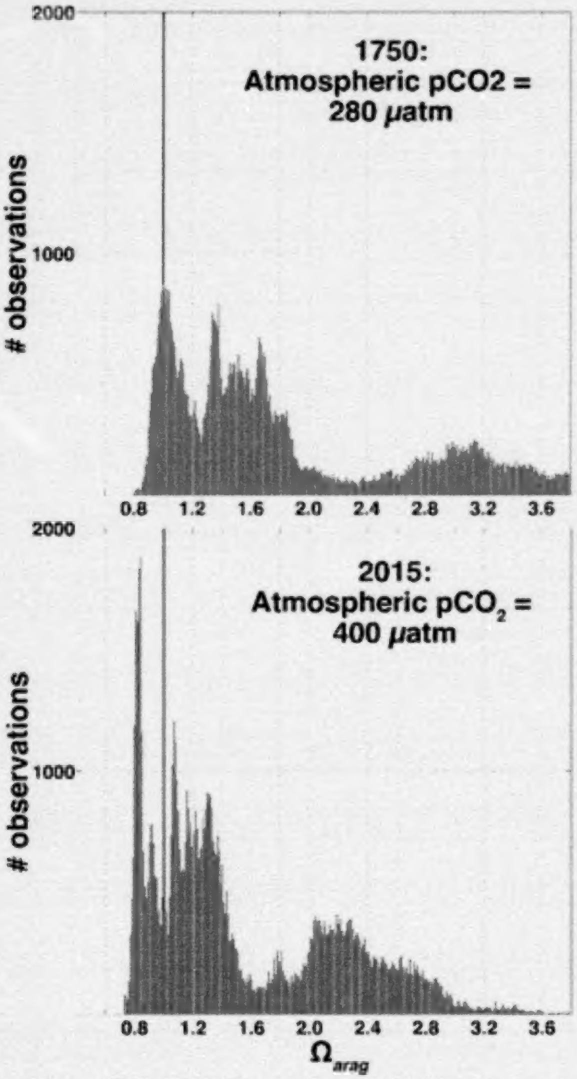

Figure 30-2. Histograms of pre-industrial (top) and 2015 (bottom) Ω_{arag} records. The vertical black line is the Ω_{arag} = 1 level below which indicates the tendency for aragonite to dissolve.

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31. TEMPERATURE AND SALINITY OBSERVATIONS IN THE STRAIT OF GEORGIA AND JUAN DE FUCA STRAIT

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31.1. Highlights

- Water temperatures in the Strait of Georgia and Juan de Fuca Strait during 2015 were up to 2 °C warmer than normal.
- A rapid and early snowmelt introduced large volumes of fresh water resulting in negative salinity anomalies in the first part of the year, and positive anomalies after the summer.

31.2. Summary

Two sources of data are used to describe changes in the temperature and salinity conditions in the Strait of Georgia (east of Vancouver Island) and Juan de Fuca Strait (south of Vancouver Island) in 2015. The first is profile data collected with a SeaBird 911 CTD during the Strait of Georgia water properties surveys (Figure 31-1). In 2015 surveys were carried out in early April, late June, and early October. The second dataset is provided by the Department of National Defence from the 71 temperature and salinity profiles it collected in 2015 with a SeaBird 19 CTD at its Maritime Experimental and Test Range (CFMETR) near Nanoose. Both sources have information available since 2000 that are compared to the 2015 conditions to identify anomalies from these 15 year average conditions.

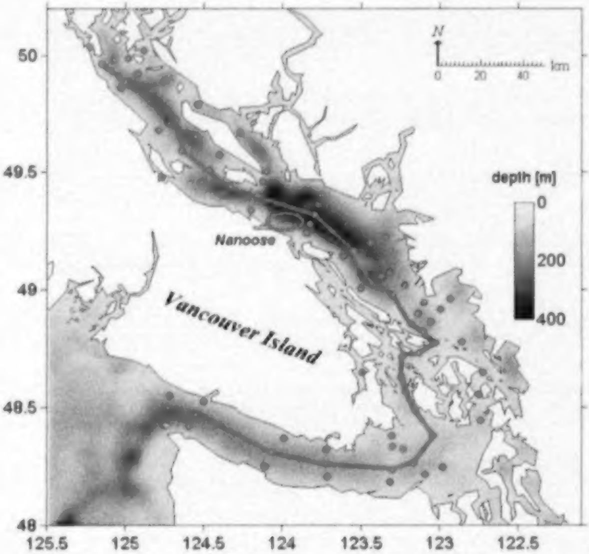

Figure 31-1. Red dots show the locations of 79 stations sampled during the water properties survey in April, June and October. The thalweg is shown as the grey line joining the deepest stations along the centerline of the survey. The red ellipse marks the area where depth profiles of temperature and salinity are collected at the Canadian Forces Maritime Experimental and Test Range (CFMETR).

The analysis of the temperature data for all three surveys showed warmer than normal conditions; the only exceptions being the deeper sections of Juan de Fuca and Haro Strait in June, possibly due to upwelled Pacific Ocean waters, and a shallow layer of surface water in the Strait of Georgia in October, likely from wind mixing. Figure 31-2 shows the typical 2015 temperature cross section for the study area, above normal temperatures throughout the water column.

The negative salinity anomaly observed during the April survey shown in Figure 31-3 reflects the high volume of fresh water in the system due to the early and rapid melting of snow in the Coastal Mountains range. Also evident is the depth of mixing in the tidally energetic region of Boundary Pass and Haro Strait.

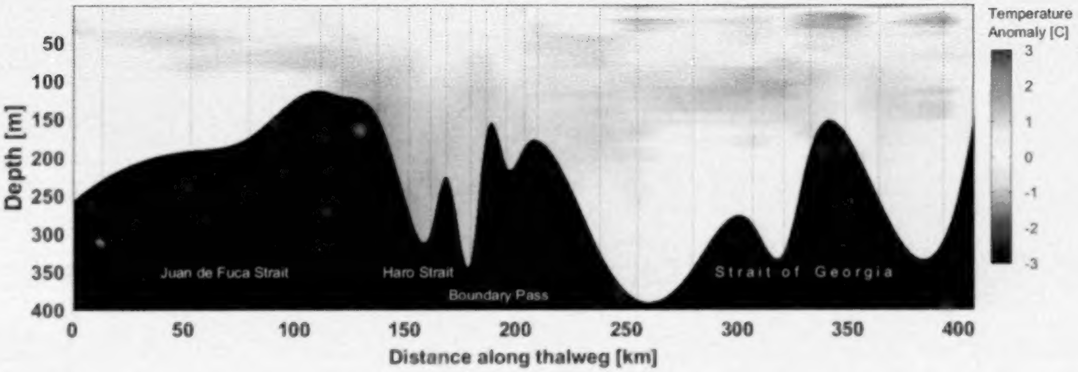

Figure 31-2. The vertical distribution of temperature anomalies along the thalweg observed in the October 2015 water properties survey.

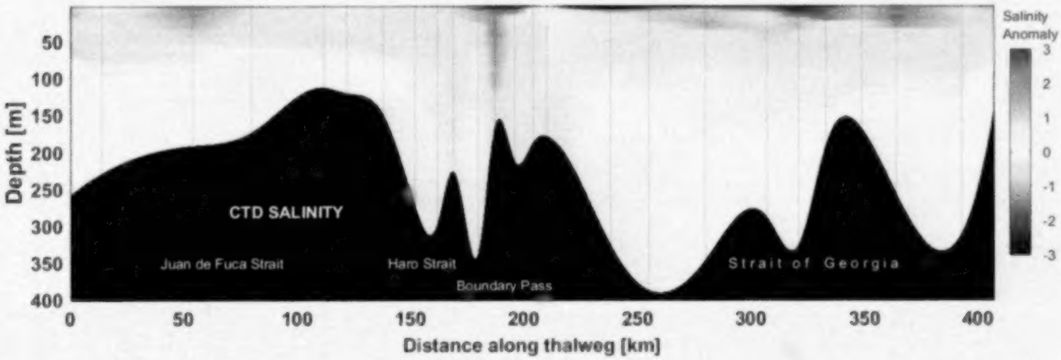

Figure 31-3. The vertical distribution of salinity anomalies along the thalweg observed in April 2015 water properties survey.

The temperature and salinity profiles collected off Nanoose are presented to show the annual variability in the central Strait of Georgia. The 2015 temperature and salinity anomalies from the 15 year dataset are shown in Figure 31-4. Early in 2015 the early and rapid snowmelt introduced significant volumes of fresh water via the Fraser River into the central Strait. The negative surface salinity anomalies are evident in the upper 100 m until June, after which the surface waters were saltier than normal due to the lower than normal Fraser River outflow. For most of 2015 the temperature anomalies show increased temperatures throughout the water column. Separate, but intense, storm events in the summer (particularly in late August) provide episodes of cooler than normal water temperatures.

The interannual variations in temperature in Figure 31-5 show the annual cycle in 2015 as different from previous years because the temperature at the start of the year was higher than usual, and the cooling typically experienced during the first few month of the year was not evident. The maximum depth averaged temperature in 2015 exceeded the record set in 2004. The 9 °C isotherm, which typically extends deeper than 150 m, and in some years to the bottom, did not exceed 50 m in 2015.

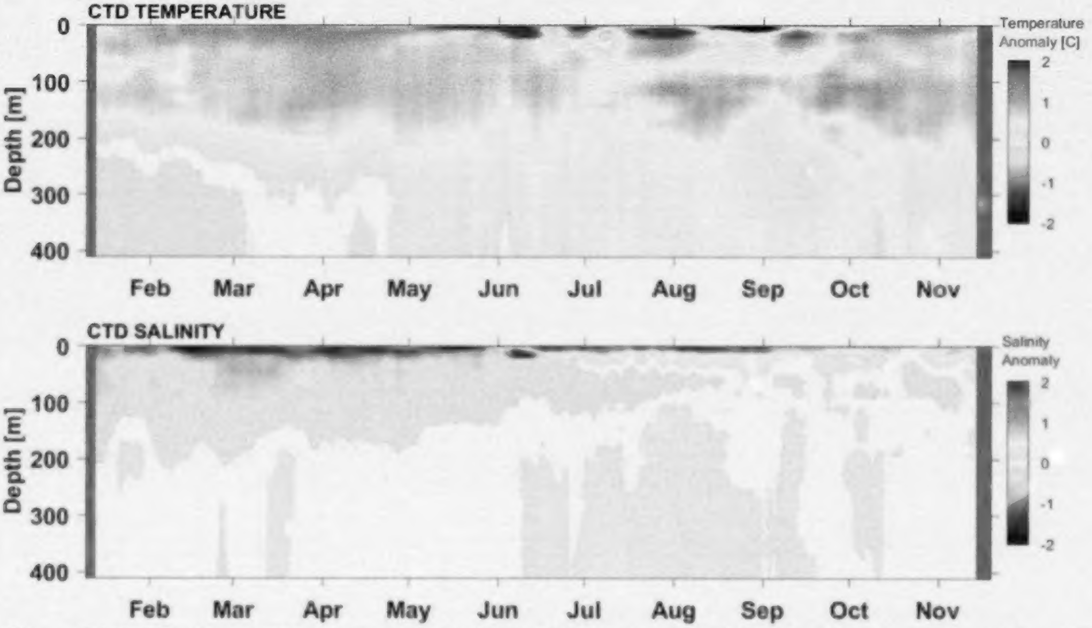

Figure 31-4. The time series of the vertical distribution of anomalies (temperature (upper) and salinity (lower)) collected in 2015 in the central Strait of Georgia near Nanoose; red indicates warmer and saltier than normal. Data source: The Canadian Forces Maritime Experimental and Test Range (CFMETR).

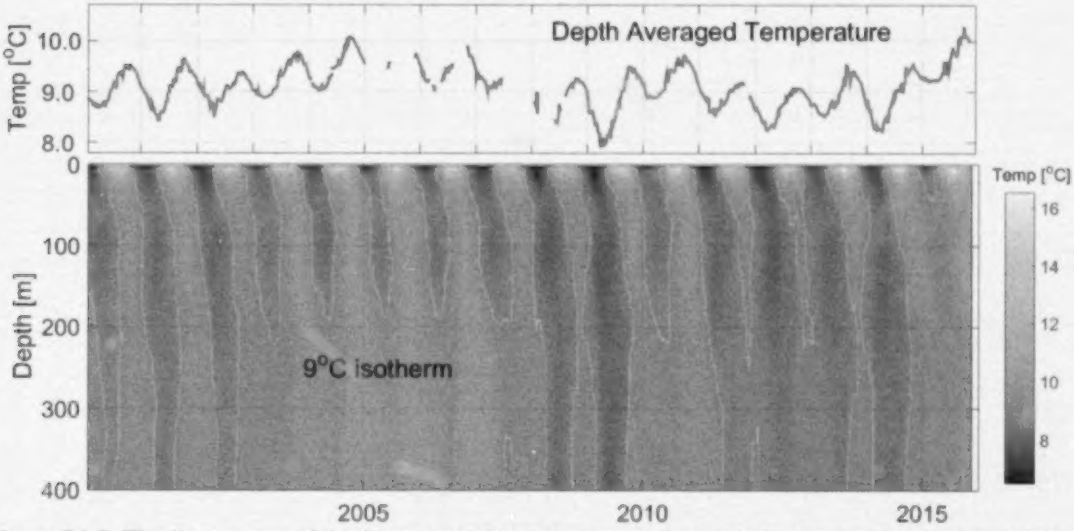

Figure 31-5. The time series of depth averaged temperature collected in the central Strait of Georgia near Nanoose (upper); the vertical distribution of these data (lower). Data source: The Canadian Forces Maritime Experimental and Test Range (CFMETR).

32. DEEP WATER AND SEA-SURFACE PROPERTIES IN THE STRAIT OF GEORGIA DURING 2015: FERRIES AND CABLED INSTRUMENTS

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32.1. Highlights

- Temperature during maximum downwelling was approximately 1.7 °C warmer at Folger Passage (97 m, west coast Vancouver Island southern shelf) than at any time during that 6-year time series. Temperature 'anomaly' indicative of the inshore arrival of the warm anomaly.
- Seasonal patterns of deep water renewal at two sites in the deep Strait of Georgia (169 and 300 m) were similar to previous years; however, winter 2014/15 was characterized by marginal cooling and stronger freshening; summer warming was the warmest for both time series and was followed by no obvious cooling at 300 m during winter 2015/16.
- Low-density (warmer) of seasonal renewal (as evidenced at 169 m) probably limited seasonal increase of dissolved oxygen (ventilation) in the deep (300 m) Strait of Georgia to some of the lowest concentrations recorded in each time series.
- Maximum phytoplankton biomass during the Strait of Georgia spring bloom was registered by ferry instruments on March 11, 2015; second earliest spring bloom for the ferry time series (extending back to 2001).

32.2. Inshore arrival of the Pacific warm water anomaly and deep water properties in the Strait of Georgia

Surface and deep-water properties are measured in real-time on the Ocean Networks Canada (ONC) cabled sea-floor arrays and instrumented ferry routes in the Salish Sea. 'Core' measurements include temperature, salinity, and dissolved oxygen concentration at all sites as well as chlorophyll fluorescence (index of phytoplankton biomass) measured along the ferry routes. All data is freely available online at http://www.oceannetworks.ca/.

The transition from upwelling to downwelling along the southern west coast of Vancouver Island starts during the late summer. The onset of downwelling on the shelf is signaled at the ONC Folger Deep (97 m; mouth of Barkley Sound) instrument platform (Figure 32-1) by the fresher, warmer and more oxygenated water characteristic of summer surface waters in the Gulf of Alaska. Dominant northward winds associated with the strengthening of the Aleutian Low pressure system drive this process. A relatively weak Aleutian Low during the 2013/14 fall-winter period is reflected by little to no warming on the shelf and indicative of the limited dissipation of summer surface heat in the central Gulf of Alaska which saw the development of the warm water anomaly (the warm "Blob"; see Figure 32-1 and Dewey et al. 2015). The inshore movement of the warm water anomaly took place in October 2014 (Ross et al. 2016) and is evidenced by temperatures approximately 1.7 °C warmer during maximum downwelling than has been previously measured at Folger Deep (Figure 32-1).

Inshore deep- and intermediate water properties in the Strait of Georgia (SoG) reflect seasonal patterns of increasing salinity and heating during the summer; due to the arrival of salty upwelled water on the shelf transiting through Juan de Fuca Strait and mixing with warm surface waters in Haro Strait (Pawlowicz et al. 2007). Winter water properties are characterized by cooling and freshening associated with deep mixing of local surface waters in Haro Strait/Gulf Islands.

Properties at the SoG East instrument platform (169 m; Figure 32-2) reflect, in part, mid-water renewal to the SoG. During the 2014/15 winter, this water was cool and fresh (as expected for the season); however, this low-density water, relative to the entire time series (extending back to 2008), was atypically warm and fresh. Cooling during the winter was minimal leading to the warmest temperatures recorded at 169 m (maximum of approximately 11.2 °C occurring on Sept 7, 2015) for the time series. Note that the timing of the seasonal increase in dissolved oxygen (starting in October 2014) was consistent with previous years, however the maximum winter concentration (4 ml/l) was the lowest measured thus far.

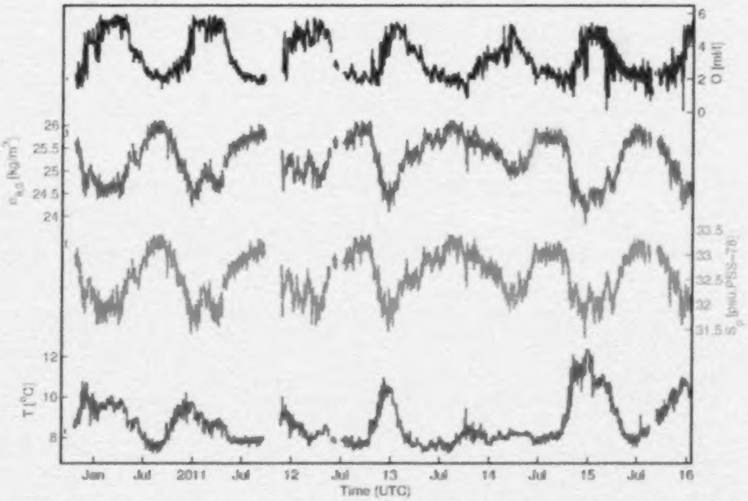

Figure 32-1. Folger passage deep platform (97 m; 48° 48.8278' N, 125° 16.8573' W). Temperature red), salinity (green), density as σ_t (blue) and dissolved oxygen (purple). The entire time-series dating back to September 2, 2009 is illustrated here. Note the near absence of warm downwelled water in late 2014, followed by the significant warm water during the downwelling of 2015.

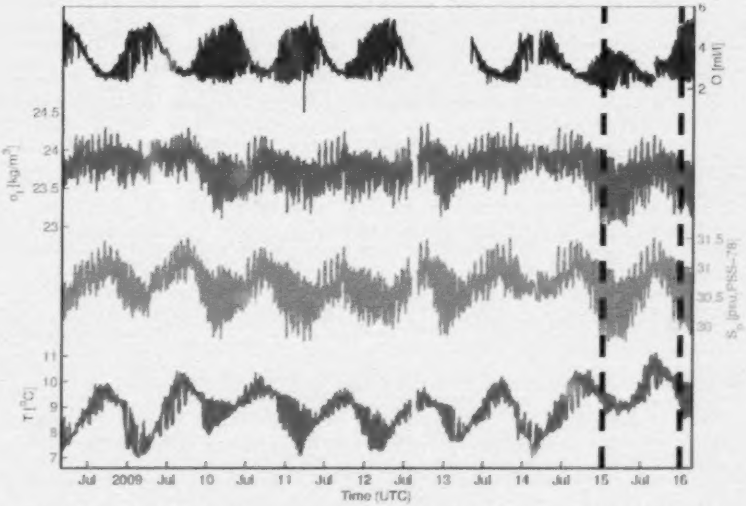

Figure 32-2. Strait of Georgia East Node (169 m). 49° 2.5575' N, 123° 19.0041' W. Temperature red), salinity (green), density as σ_t (blue) and dissolved oxygen (purple). The entire time-series dating back to February 28, 2009 is illustrated here.

The seasonal pattern of water properties at 300 m (SoG Central Node; Figure 32-3) is similar to the mid-basin platform at SoG East: Typical winters are characterized by cooling/freshening due to top down flux; and summers characterized by warming/increased salinity due primarily to deep water renewal events. Seasonal patterns of dissolved oxygen in the deep basin (SoG Central) are however, much more closely tied to monthly deep-water renewal events than at 169 m. These renewal events are marked by abrupt spikes in all properties (Masson 2002).

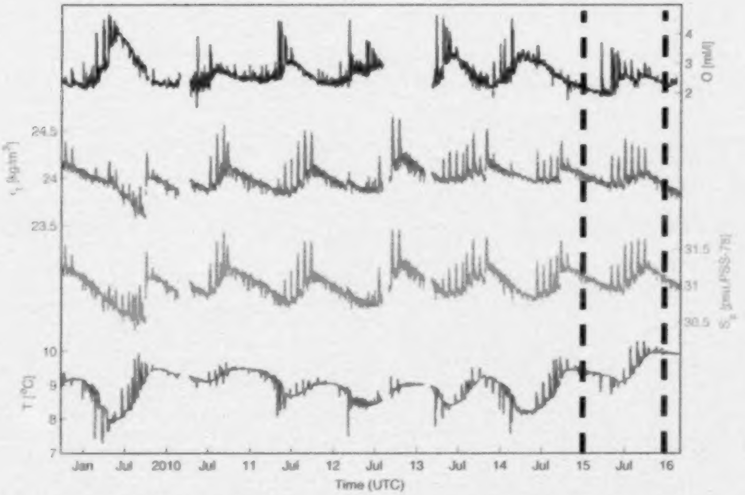

Figure 32-3. Strait of Georgia Central Node (300 m). 49° 2.4034' N, 123° 25.5471' W. Temperature red), salinity (green), density as σ_t (blue) and dissolved oxygen (purple). The entire time-series dating back to September 24, 2008 is illustrated here.

Dissolved oxygen concentrations started to increase in late April - early May 2015 at 300 m; however the seasonal maximum was relatively low (~2.5 mL/L). Low dissolved oxygen at 300 m may reflect limited ventilation from the atypically warm and fresh waters above. As at 169 m, winter cooling at 300 m was marginal, resulting in a "warm" winter comparable to the winter of 2010 (also an El Niño year, winter minima in both years was approximately 9.2 °C). Unlike 2010, however, the summer warming was greater, yielding the highest bottom water temperatures (10.05-10.1 °C) for this time-series. Note, winter cooling expected to start in late 2015 did not occur and temperatures remain at approximately 10 °C through to early April 2016.

32.3. 2015 Spring Bloom in the Strait of Georgia.

High-resolution monitoring of sea-surface properties by instruments installed aboard the BC Ferries vessels, the *Queen of Alberni* and *Spirit of Vancouver Island*, captured the development of the spring phytoplankton bloom in the southern Strait of Georgia in 2015 (Figure 32-4). The bloom started at about the same time both inside and outside the Fraser river plume during the first week of March and maximum chlorophyll fluorescence was measured on March 11, 2015. Timing of the spring phytoplankton bloom can vary by up to 6 weeks (Allen and Wolfe 2013; Figure 32-4) with a mean date of March 25. Thus, the 2015 spring bloom was relatively early, and was the second earliest (the earliest being late February 2005) measured by ferry systems since 2001. The 'early' timing of the 2015 spring bloom stands in contrast to the relatively 'late' bloom of 2014 which peaked on April 9, 2014 (Dewey et al. 2015).

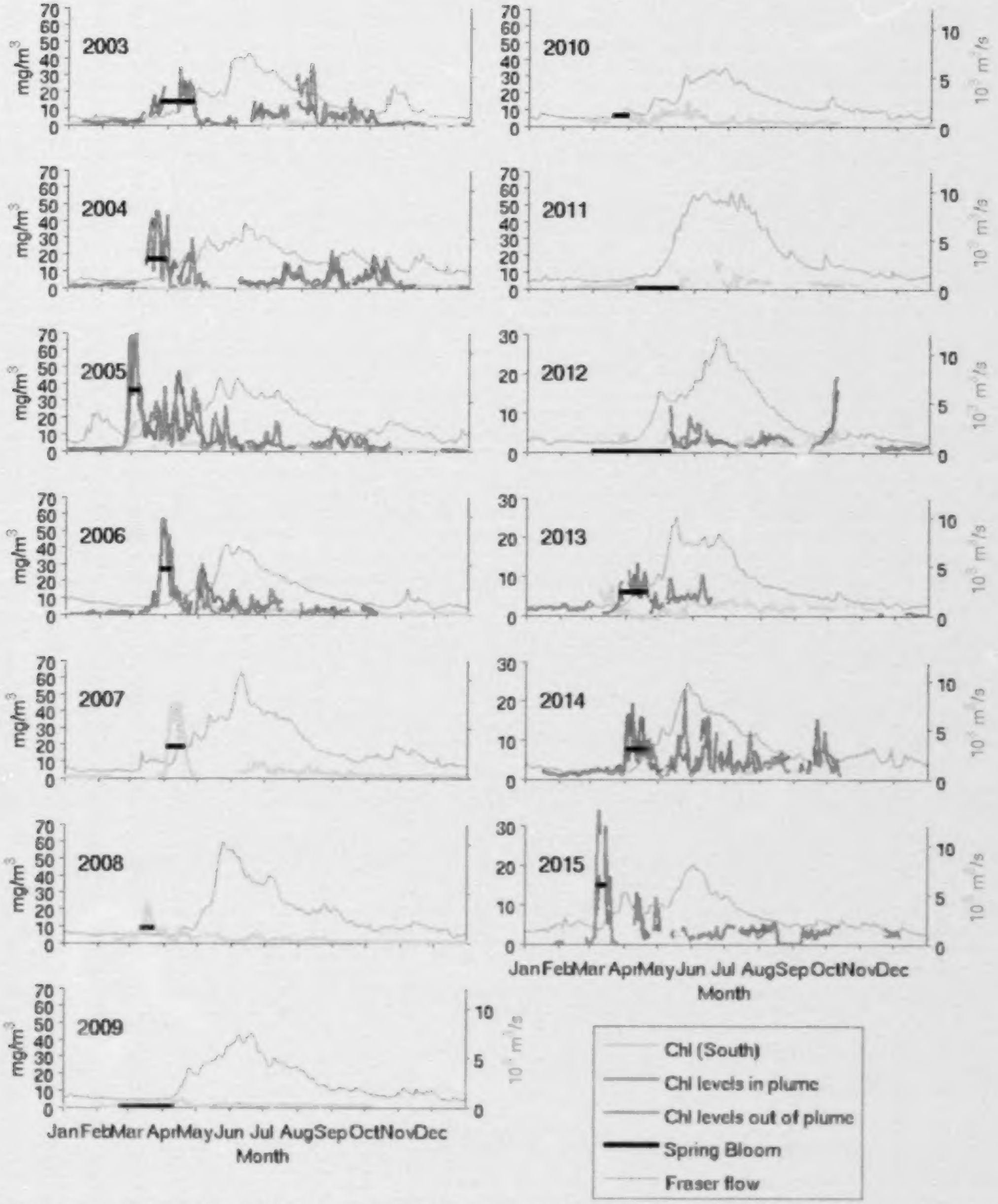

Figure 32-4. Time series of phytoplankton biomass (chlorophyll fluorescence) inside and outside of the Fraser River plume as measured from instrumented BC ferries transiting between Duke Point and Tsawwassen (dark green and red) and Swartz Bay and Tsawwassen (light green). Fraser River discharge (right-hand axis) is superimposed over the annual phytoplankton biomass time-series. Black lines show bloom timing (presumed in 2009. 2011, 2012).

1.4. References

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33. TIMING OF THE SPRING PHYTOPLANKTON BLOOM IN THE STRAIT OF GEORGIA, 2015 AND 2016

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33.1. Highlights

- Timing of the spring phytoplankton bloom in the Strait of Georgia is estimated for 2015 and 2016 from a computer simulation model.
- Model results for 2015 predicted the bloom would occur in mid-March, which was as observed. This was the earliest spring bloom in this region since 2005.
- Model results for 2016 predicted the bloom would occur in late-March, which was as observed.

33.2. Summary

The timing of the spring phytoplankton bloom is not a good measure of all interannual variability in any setting, including the Strait of Georgia. However, it is a good measure of biological spring. In the Strait of Georgia spring bloom timing is highly variable, ranging from late February to mid-April. Changes in the timing have been linked to the success of herring larval recruitment in the Strait of Georgia (Schweigert et al. 2013) and to summer zooplankton community composition in Rivers Inlet, a nearby fjord (Tommasi et al. 2013).

The timing of the spring bloom in the Strait of Georgia is controlled by the light availability to phytoplankton. The interannual variability in the amount of light phytoplankton receive depends on the amount of light penetrating into the water and the depth of the phytoplankton. The latter is controlled by the depth of mixing. The amount of incoming light into the Strait of Georgia is most influenced by the cloud fraction. The depth of mixing is mainly controlled by the wind strength. In this well-stratified system, the incoming freshwater from the river plays a secondary role. More river flow does increase the stratification and thus decrease the mixed layer depth. However, it also increases the advective loss of phytoplankton (Collins et al. 2009).

We use results from a computer model coupling the physics and lower trophic levels in the Strait of Georgia and compare those results to observational data collected on ferries (Sastri et al. 2016). The model has been developed and can successfully model the timing of the spring bloom (Collins et al. 2009) which has allowed a hindcast of the timing since 1969 (Allen and Wolfe 2013, Figure 33-1)

33.3. Model/Data Comparison

A recent compendium of data from all ferry systems in the Strait of Georgia has been compiled. This includes 1) STRATOGEM data, 2) Institute of Ocean Sciences Data from Jim Gower, and 3) recent Ocean Networks Canada data. The first and third of these are from the Tsawwassen/Duke Point route; the second is from the Tsawwassen/Swartz Bay route. Data are extracted and averaged for in and out-of-plume for 1 and 3. Bloom timing in and out-of plume is the same for all years (when both are available; to the resolution we see). In and out of plume matters more in the summer. For 2, data were averaged over the southern Strait of Georgia section of the route.

Observations and model results overlap (Figure 33-2) except in 2008, 2010 and 2014. In 2010, the observations are difficult to interpret (Sastri et al. 2016). In 2014, the model is slightly earlier, in 2008 it is quite late. In 2015 and from preliminary observations for 2016, the model predictions are accurate.

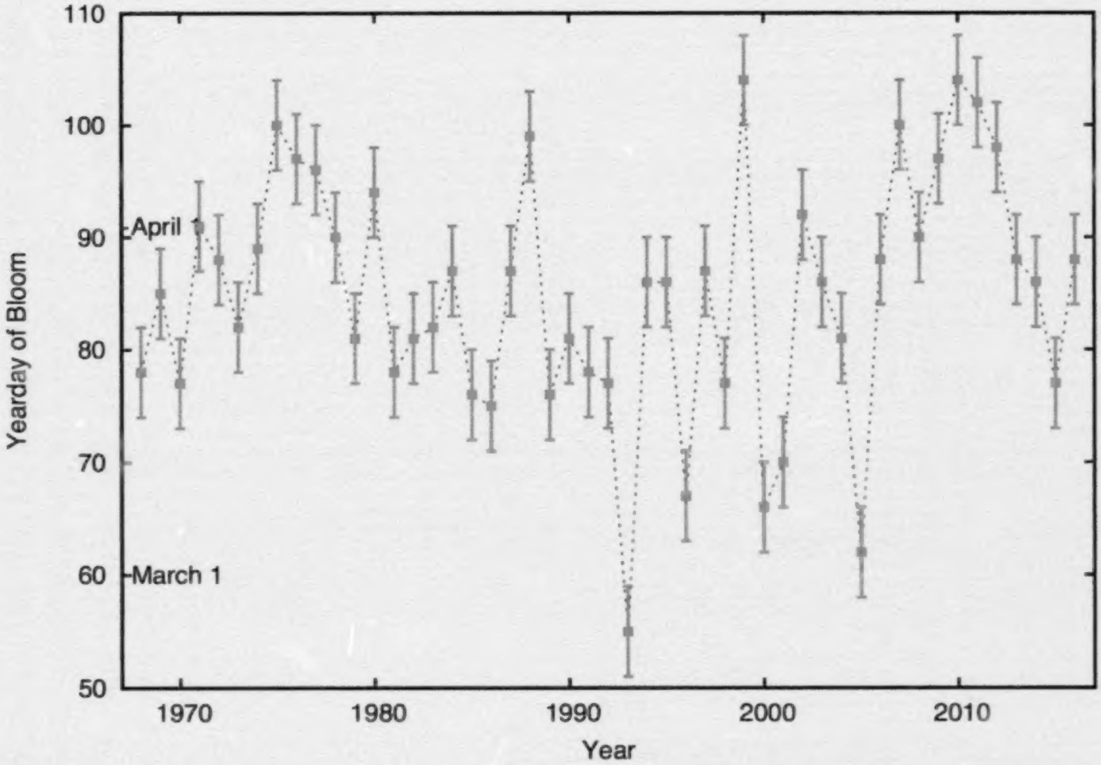

Figure 33-1. A 48 year time series of the timing of the spring phytoplankton bloom according to the model. The spring bloom in the model is defined as the time of the peak phytoplankton concentration (averaged from the surface to 3 m depth) within four days of the average 0-3 m nitrate concentration going below 0.5 μM for two consecutive days. Note the five very early blooms that all occurred between 1993 and 2005 and the persistently late blooms from 2006 to 2014.

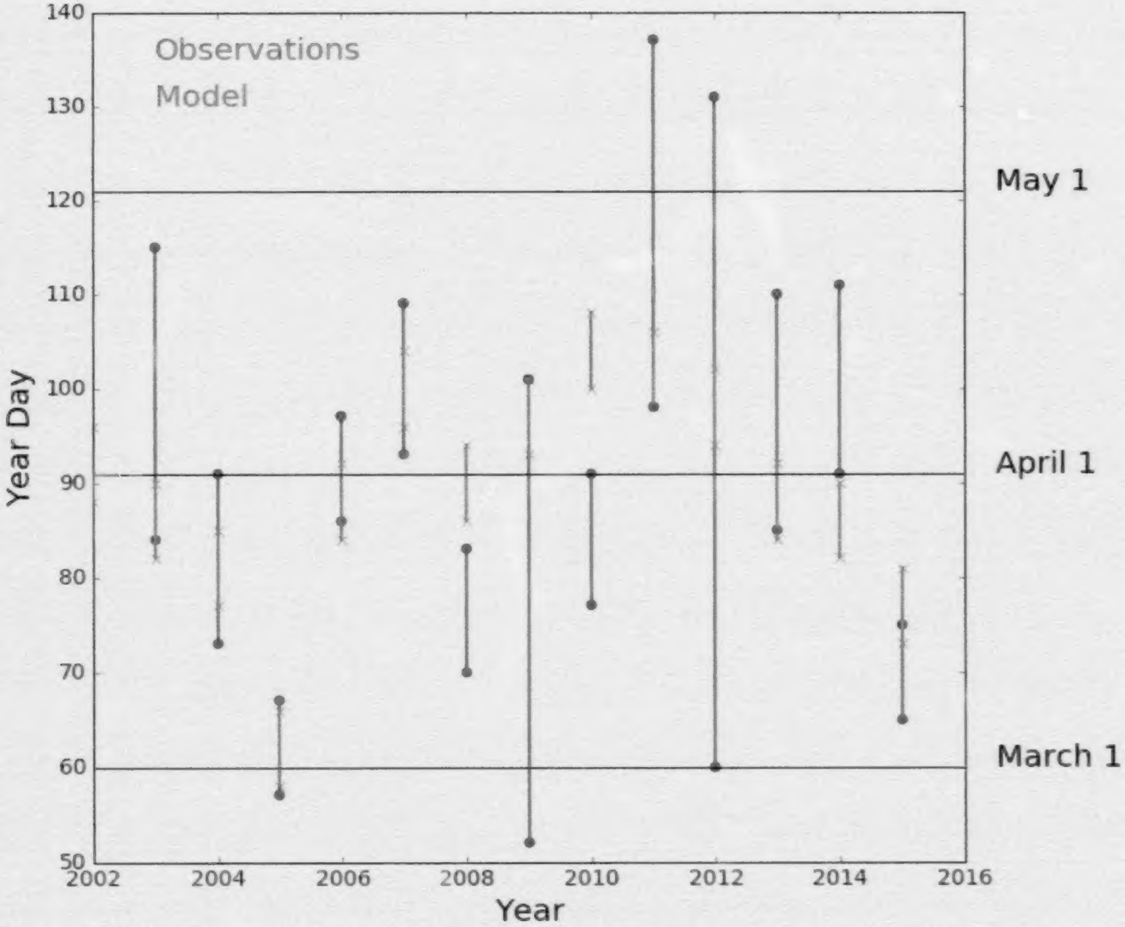

Figure 33-2. A time series showing the comparison between ferry observations (green) and model results (red). Ferry observations of bloom timing are defined by the period during which Chlorophyll fluorescence values are more than 50% of the peak value, except during 2009, 2011, and 2012 where the gaps in the ferry time series make such a determination impossible, however we do know that the actual bloom occurred at some unknown time within the indicated interval. Model observations are peak of the spring bloom (see exact definition in Figure 33-1 caption) plus and minus the 4 day estimated error.

33.4. 2015 Spring Bloom According to the Model

January and February 2015 were warm and the Fraser River flow was very high for this time of year. A period of low cloud amounts in late February led to rapid growth (Figure 33-3). The peak of the spring bloom (March 17 from the model) was the earliest since 2005 (Figure 33-1).

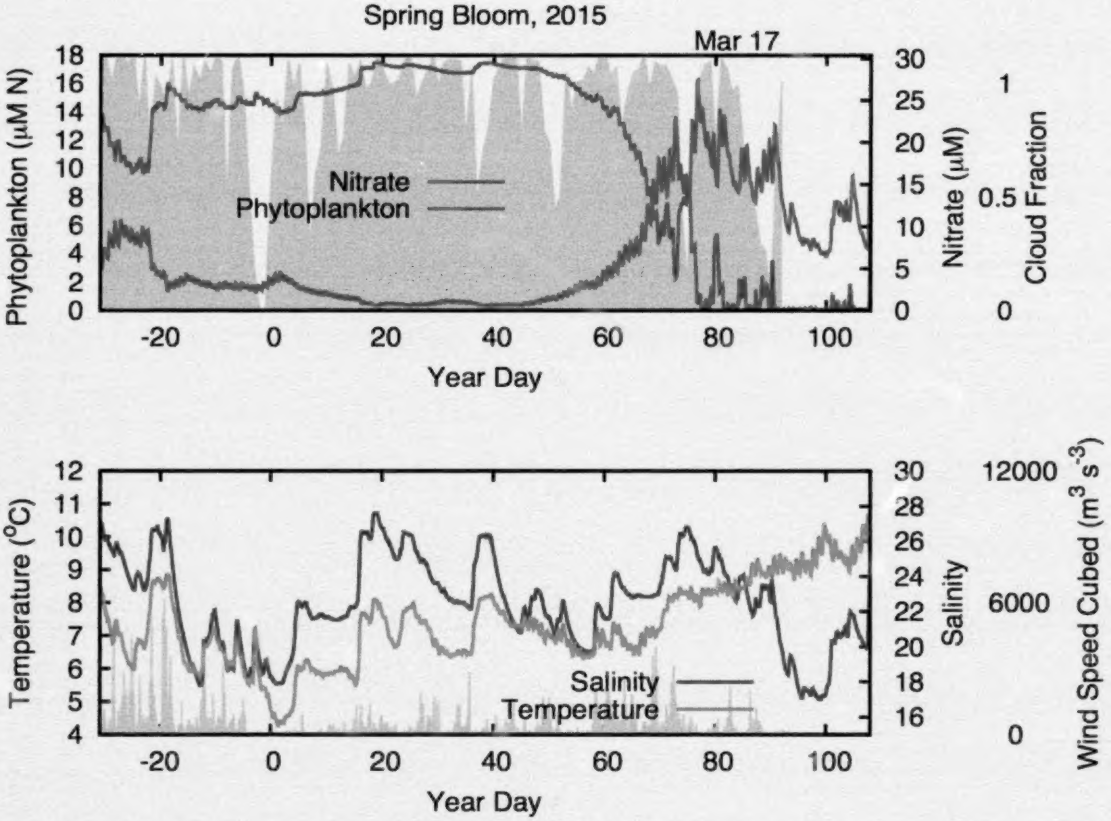

Figure 33-3 (From Allen and Latornell 2015). Hindcast of the 2015 spring bloom and related conditions in the Strait of Georgia. The lower panel shows temperature (in red) and salinity (in blue) averaged over the upper 3 m of the water column; in grey is the wind-speed cubed which is directly related to the strength of the mixing. One can clearly see the mixing associated with the storm about day 38; salinities increase as deeper high salinity water is mixed into the surface waters. The top panel shows phytoplankton biomass (in dark red) and nitrate (in green); in grey is the cloud fraction averaged over the day. One can see the influence of low wind, low cloud periods such as that after day 42. Here phytoplankton biomass steadily increases and nitrate decreases. The 2015 spring bloom (day 76/March 17 hindcast, March 13-15 observed) was the earliest since 2005. Plots span the period December 1, 2013 to April 18, 2015.

33.5. 2016 Spring Bloom According to the Model

Winter 2015-2016 again was warm, but not as warm as the previous year and so precipitation fell as snow on the mountains not as rain which it did in 2015. Timing was near typical until a number of strong storms (with very strong winds) on February 17, 23, March 10 and 22, delayed the bloom to make it moderately late: March 28 (Figure 33-4).

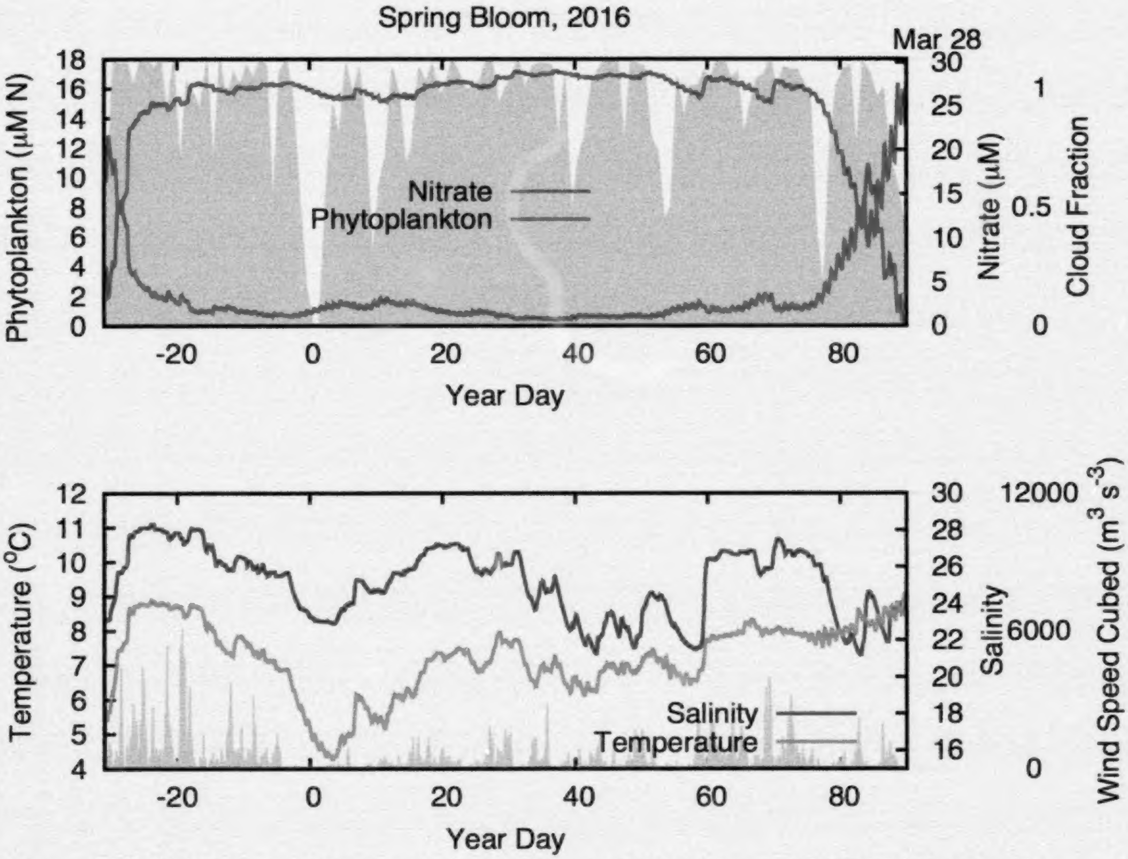

Figure 33-4. Hindcast of the 2016 spring bloom and related conditions in the Strait of Georgia. See Figure 33-3 caption for parameters plotted. The 2016 spring bloom (March 28 hindcast) was a week later than the mean (March 21) because of four strong storms in February and March. See the increases in salinity and nitrate on days 48, 54 and 70 (February 17, 23 and March 10) and the decreases in phytoplankton on days 54, 70 and 82 (February 23, March 10 and 22). Plots span the period December 1, 2015 to April 1, 2016.

33.6. Details of the coupled-biophysical Model (from Allen and Latornell 2015)

The model is a vertical-mixing layer model forced by observed winds at Sand Heads, observed air temperature and humidity at Vancouver International Airport (YVR), Fraser River flow at Hope and Englishman River flow at Parksville (Environment Canada 2015a,b). The latter is multiplied by 55 to represent all river flows into the Strait other than the Fraser River.

Cloud fraction is interpreted based on the weather description and the historical average cloud fraction to weather, done by month for the most common weather descriptions. The physical model is based on the Large et al. (1994) KPP-model with an estuarine circulation model added (Collins et al. 2009). To model a spring bloom, only a simple nitrate-diatom biological model is used. The diatom growth parameters are taken from the literature based on the first phytoplankton to bloom in the Strait (*Thalassiosira* spp.). The model zooplankton concentration was taken from observations (Sastri and Dower 2009) and the model was tuned by adjusting the phytoplankton growth rate (Allen and Wolfe 2013) within the range measured in the laboratory. The model was tuned, within 4 days, for the spring blooms of 2002-2005 for which detailed observations were made as part of the STRATOGEM project (Allen and Wolfe 2013).

Predictions for the 2017 bloom will be available, starting in early 2017, at http://salishsea.eos.ubc.ca/bloomcast/spring_diatoms.html.

33.7. References

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34. CHLOROPHYLL PHENOLOGY IN THE SALISH SEA: SPATIAL AND TEMPORAL DATA FROM OCEAN COLOUR SATELLITES IMAGERY

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34.1. Highlights

- The satellite chlorophyll climatology (2003-2015) indicates the seasonality in the Salish Sea, where lower values (approximately 2.0 mg m^{-3}) are present at both beginning and end of year corresponding to winter conditions, and average higher *Chla* values (approximately 10.0 mg m^{-3}) are present in the spring and summer periods.
- The *Chla* time series also shows that late summer and fall blooms occur. Fall blooms are more prevalent in the central region where *Chla* exceeding 5.0mg m^{-3} occurs after September for almost every year.
- Based on the bloom criteria for the time of initiation in the central Salish Sea, the *Chla* time series indicate that, on average, the spring bloom initiation is on March 29 (±4 days).
- 2015 had an earlier bloom on February 22 (±4 days) similar to 2005. These years exhibited the earliest blooms in the analyzed time series.

34.2. Summary

There is a need for improved long-term spatial-temporal monitoring, evaluation and reporting of dynamic processes such as ocean productivity, critical habitats, and fisheries in coastal environments, given the effects of increasing human pressures and a changing climate (Stelzenmüller et al. 2013). To assess the impact of bottom-up forcing on fish populations, for example, there is a specific need of long-term spatial-temporal productivity data (Perry and Masson 2013). Traditional methods for monitoring coastal water properties typically rely on *in situ* sampling from ship or buoy based systems. Data derived from satellite remote sensing offer an unparalleled tool for synoptic biomass sampling associated with high sampling frequencies. This report provides the analysis of chlorophyll yearly dynamics and bloom initiation for the Salish Sea based on a time series (2003-2015) of MODIS imagery.

Image data (Level 1a) were accessed from NASA's OceanColor web portal, and processed in the SeaDAS (Seawifs Data Analysis System) environment. All available good quality MODIS-Aqua images from January 2003 through July 2015 at 1 km^2 nadir spatial resolution were processed. As a first step, the images were atmospheric corrected using the Management Unit of North Seas Mathematical Model (MUMM) using SWIR bands. The Aerosol Optical Thickness (AOT) at 443 nm, derived from the Aerosol Robotic Network (AERONET) for atmospheric measurements, acquired within +/- 15 minutes of imagery acquisition were compared to the atmospheric corrected imagery (n=684) resulting in a $R^2=0.5$, slope=1.02 and RMSE=7.04%) for aerosol optical thickness at 440 nm. In the second step, the OC3M chlorophyll algorithm was applied to the atmospheric corrected imagery followed by flags corresponding to high solar zenith angle, high sun zenith angle, straylight, and pixels with negative reflectance values in the blue, due to obvious atmospheric correction failure. The derived satellite chlorophyll

concentrations (*Chla*) were validated with *in situ* data from the DFO Institute of Ocean Sciences database and our own HPLC measurements showing the statistically significant performance of the MUMM+SWIR method (R^2=0.69, slope=0.89, $_{log}$RMSE=0.33, n=16 for +/- 1 hour match-up; R^2=0.55, slope=0.77, $_{log}$RMSE=0.36, n=83 for +/- 8 hours match-up).

After validation, all *Chla* images were binned to derive mean 8-day *Chla*. Timing of bloom initiation was defined as the yearday (+/- 4 days) where *Chla* were greater than two consecutive measurements over the annual median plus 5% or the yearday of the first *Chla* estimate greater than 5.0 mg m^{-3} (similar to Schweigert et al. 2013 and Siegel et al. 2003).

The chlorophyll climatology (2003-2015) indicates the seasonality in the central Salish Sea (Figure 34-1), where elevated and variable concentrations in the spring, summer, and fall, and lower concentrations in the winter, similar to findings by other research for this region (Halverson and Pawlowicz 2013, Masson and Peña 2009, Schweigert et al. 2013). *Chla* are generally lower from November to February when concentration are on average 1.5 mg m^{-3} and 3.1 mg m^{-3} for the northern and central regions, respectively. Spring, summer and fall show average concentrations ranging 3.0-6.0 mg m^{-3} and 4.0-9.5 mg m^{-3} for the northern and central region, respectively. In general the months with highest concentrations are April through June. However, fall blooms happen in the central region where *Chla* exceeding 5.0 mg m^{-3} occurs between September and October.

The time series analysis of the MODIS Aqua imagery shows that on average, the spring bloom initiation day (YD_{init}) is on March 29 (day=88 ±4 days) and on March 20 (day=80 ±4 days) for the central and northern Salish Sea, respectively (Figure 34-2). For the central region, the latest spring bloom initiation happened in 2010 in mid-April, and the earliest in 2005 and 2015 when YD_{init} dates happened in February 22 (±4 days) for both years.

Figure 34-3 illustrates the spatial and temporal differences between 2014, when the bloom started in the first week of April, and 2015, when the bloom stared in the third week of February.

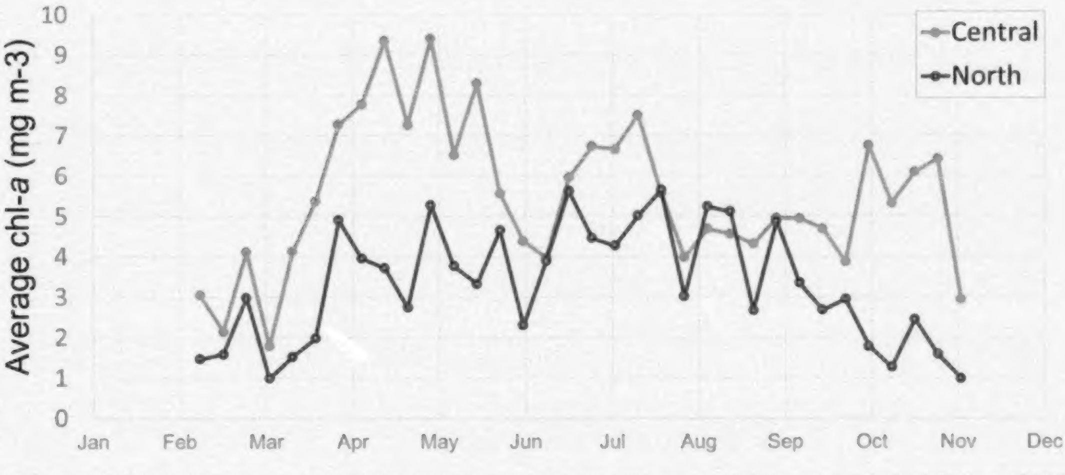


Figure 34-1. Weekly-averaged Chlorophyll time series for the central and northern Salish Sea (2003-2015).

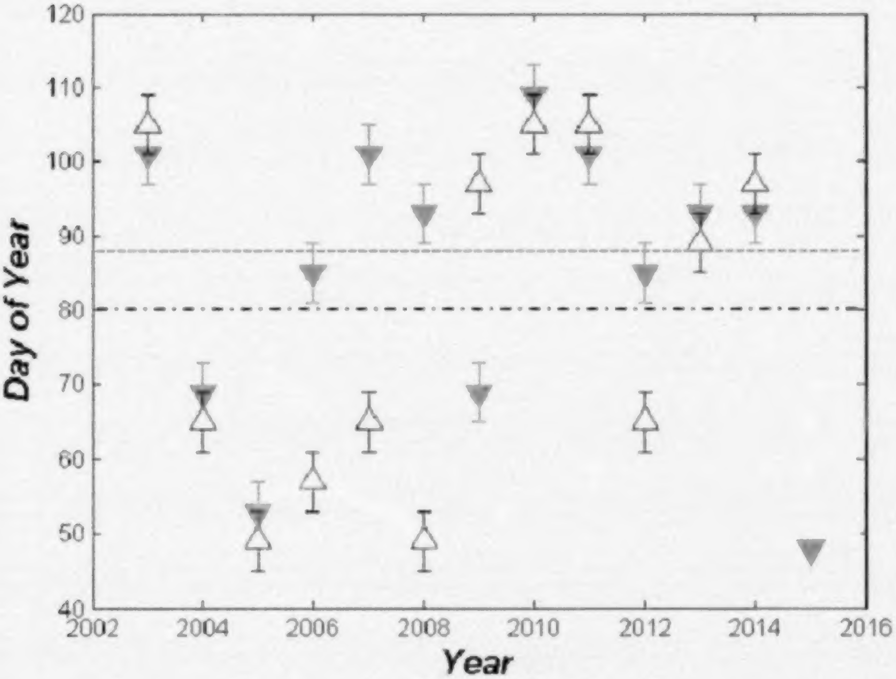
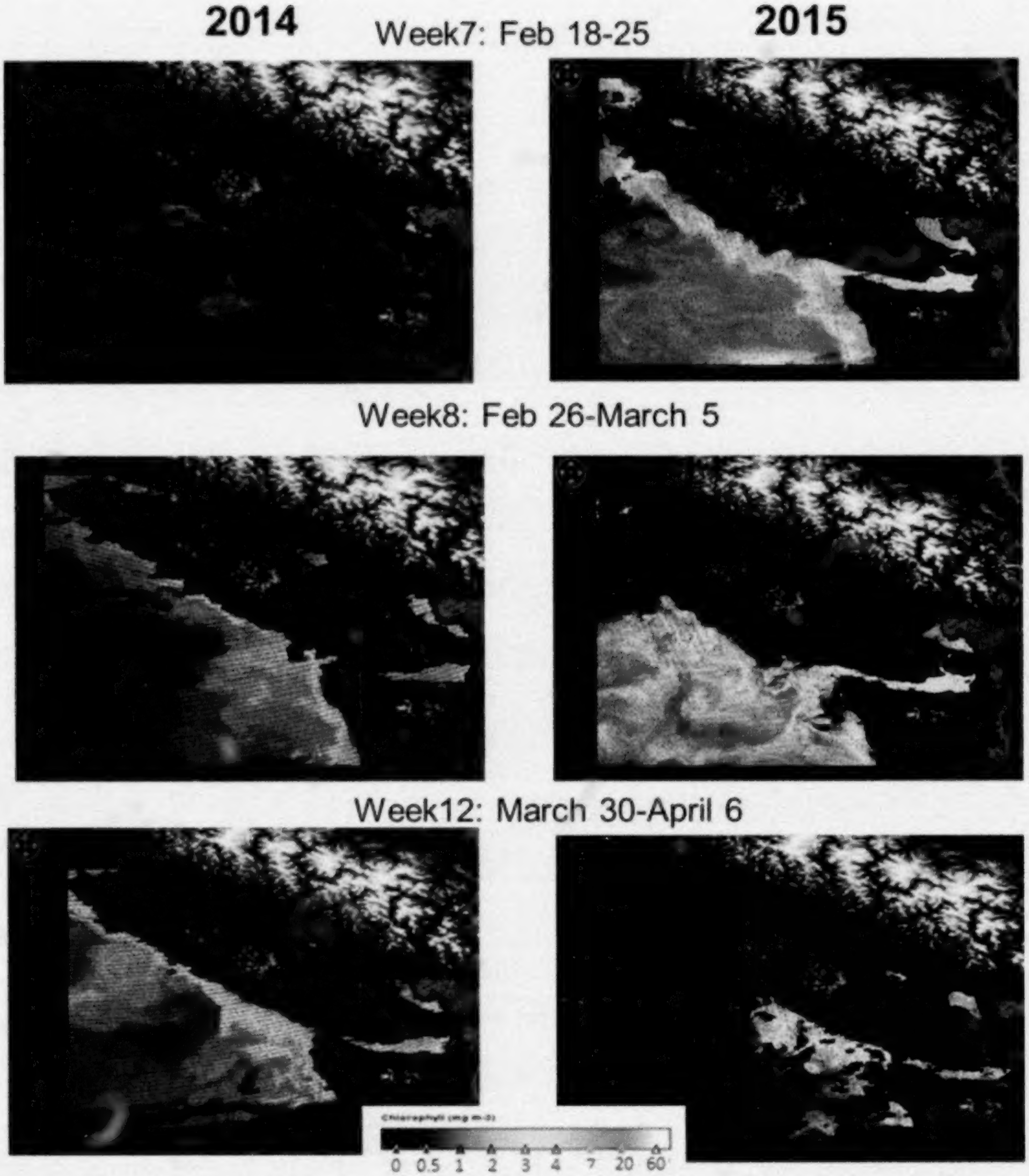


Figure 34-2. Spring bloom start dates for the central (red triangles) and northern (black triangles) Salish Sea. Lines represent average bloom initiation considering the entire time series.



2014 Week7: Feb 18-25 **2015**

Week8: Feb 26-March 5

Week12: March 30-April 6

Chlorophyll (mg m-3)
0 0.5 1 2 3 4 7 20 60

Figure 34-3. Spatial Chla in the Salish Sea and west coast of Vancouver Island showing low and high concentration in February for 2014 and 2015, respectively. First week of April shows high concentrations in both 2014 and 2015.

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35. STRAIT OF GEORGIA JUVENILE HERRING SURVEY

Jennifer Boldt[1], Matt Thompson[1], Charles Fort[1], Chris Rooper[2], Jake Schweigert[3], Terrance J. Quinn II[4], Doug Hay[3] and Tom Therriault[1]

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35.1. Highlights

- An index of the relative biomass of age-0 herring in the SOG was lower and stable during 2013-2015, compared to the peaks within the time series.
- Age-0 herring were heavier for a given length in 2015.
- The age-0 herring index may be a leading indicator of the number of recruits joining the population 2.5 years later and the amount of prey available to predators in the SOG.

35.2. Description of indices

The SOG juvenile herring and nearshore pelagic ecosystem survey, supported in part by the Pacific Salmon Foundation, is a long-term monitoring program that samples the nearshore pelagic fish community, the zooplankton community, as well as the physical water column properties (e.g., temperature, salinity, oxygen). One goal of the survey is to provide an index of the relative biomass (abundance) of age-0 herring and relate it to abundance of age-3 herring in the stock assessment model. This index may also represent trends in potential prey availability to Coho and Chinook Salmon and other predators. The methods of calculating an index of age-0 herring from the survey data collected to date are described in Boldt et al. (2015). There are multiple indices calculated in the report, but since temporal trends are similar among indices, only one is presented here.

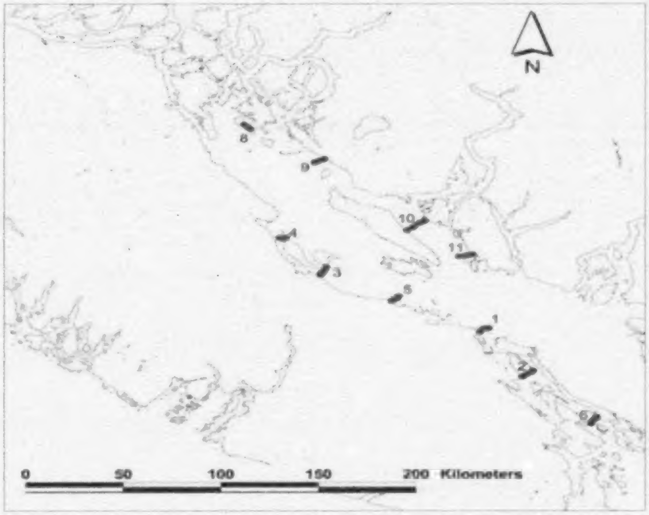

Figure 35-1. Purse seine set locations along the 10 core transects of the Strait of Georgia juvenile herring survey.

There are ten core transects, each with 3 to 5 core stations, distributed at approximately equal intervals around the perimeter of the SOG that have been consistently sampled during the autumn since 1992 (except 1995; Thompson et al. 2013; see Thompson et al. 2003 for detailed survey design and methods; Figure 35-1). Sampling was conducted after dusk when herring were near the surface and, generally, one transect was sampled per night over the course of a 4 to 7 hour period. The stations were sampled with "blind" (undirected) purse seine sets (sets were made at predetermined stations). Catch weights were estimated and all fish (or a subsample of fish) were retained for sampling in the laboratory, with the exception of large predator species (e.g. adult salmon and flatfish), which were individually measured in the field. In the laboratory, fish from each station were sorted to species and up to 100 individual age-0 herring were weighed and measured. Herring were measured to standard length (nearest millimeter) and were between 54 and 125 mm long in all years sampled. The age-0 herring index was calculated using Thompson's (1992) two-stage (transect, station) method and variance estimator to calculate the mean (and associated variance) of juvenile herring survey catch weight CPUE (for details see Boldt et al. 2015). In addition, herring condition was calculated as residuals from a log-transformed length-weight regression.

35.3. Status and trends

Estimates of age-0 catch weight CPUE (the index) varied annually, with no overall trend during 1992-2015 (Figure 35-2). The age-0 herring index tended to peak every two or three years, with the peaks occurring in even years during 2004-2012. The index was relatively low and stable during 2013-2015, compared to the peaks within the time series. High estimates of variability are associated with peak estimates; the survey CV is 0.47. Age-0 herring condition increased since 1997, with positive residuals since ~2005 (Figure 35-3).

35.4. Factors causing trends

Factors that can potentially affect herring abundance, distribution, and condition include zooplankton prey availability (including timing), predator and competitor species abundance, environmental factors, and disease. For example, herring recruitment and survival has been linked to water temperatures (Tester 1948, Ware 1991) and bottom-up control of production (Ware and Thompson 2005, Perry and Schweigert 2008, Schweigert et al. 2013).

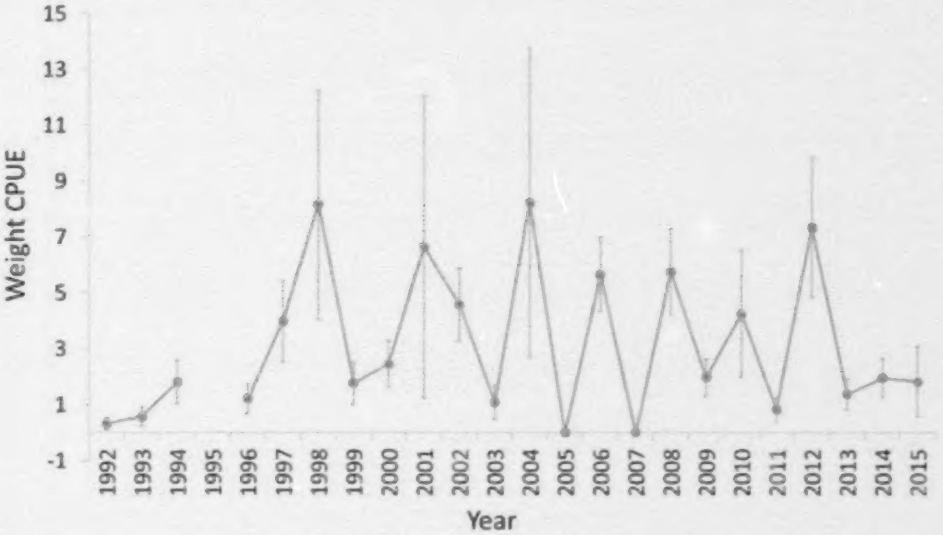

Figure 35-2. Mean catch weight per-unit-effort (CPUE) of age-0 herring caught in the Strait of Georgia juvenile herring survey at core transects and stations during 1992-2015 (no survey in 1995; Boldt et al. 2015). Standard error bars are shown.

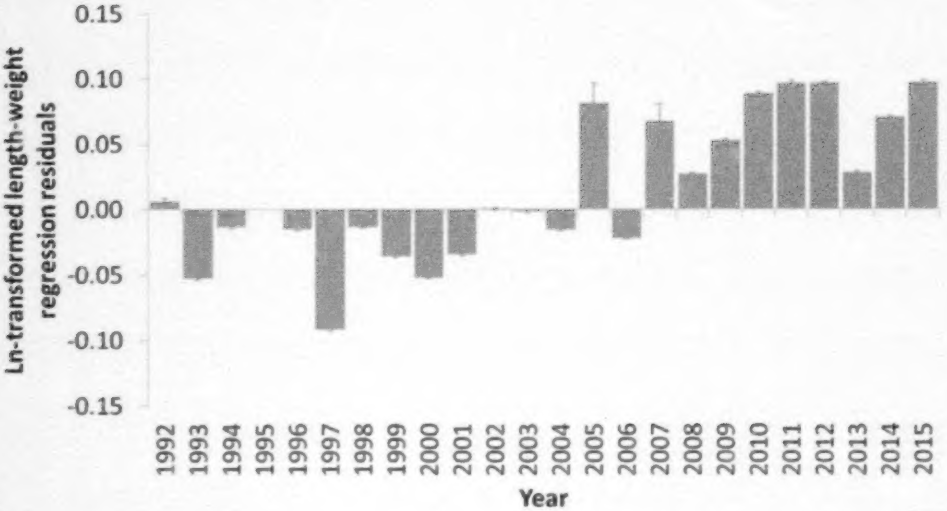

Figure 35-3. Mean age-0 herring condition (residuals from a log-transformed length-weight regression) from the Strait of Georgia juvenile herring survey, 1992-2015 (no survey in 1995; Boldt et al. 2015). Standard error bars are shown.

35.5. Implications of trends

Boldt et al. (2015) and previous analyses (Schweigert et al. 2009) showed that age-0 herring survey indices are correlated with the abundance of age-3 recruits (2.5 years later) as estimated by the age-structured stock assessment model (J. Cleary, DFO, personal communication). This supports the hypothesis that age-0 herring indices may be indicative of the relative amount of herring in the SOG and the number of recruits joining the population 2.5 years later. Pacific Herring are prey for piscivorous fish, marine mammals, and seabirds and are important commercial species in British Columbia's coastal waters. Changes in herring abundance may affect availability to commercial fisheries as well as the survival of predators, such as Coho and Chinook Salmon. Boldt et al. (2015) state that increased age-0 herring condition indicates that "fish are heavier for a given length and may be more energy dense (Paul et al. 1998, Boldt and Rooper 2009). Fish that have a higher energy density have an improved chance at surviving reduced feeding opportunities during winter (Paul et al. 1998, Foy and Paul 1999) and present a more energy-rich prey for predators". Understanding trends in the populations of small pelagic fish species and factors that affect their abundance and condition requires long-term monitoring of the nearshore pelagic ecosystem.

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36. STRAIT OF GEORGIA JUVENILE SALMON

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36.1. Highlights

- The survey catch of juvenile Coho Salmon in September 2015 remained above average (data collected since 1998) suggesting good returns in 2016. In addition, the average size was even greater than in 2014. If size in September relates to returns, this would be a good signal for the 2016 return.
- The catch of late ocean entrants (Harrison River Sockeye Salmon and Chinook Salmon from the South Thompson) in September 2015 was lower than average for the past few years. This suggests a poor year class for this stock.
- The projected returns based on these observations within the Strait of Georgia have to be taken with caution as the unusual conditions on the west coast of Vancouver Island during the last two years have not been observed previously and therefore it is not known how they will effect these salmon during their ocean rearing periods. Poor returns of Coho Salmon in 2015 suggest that, at least for this species, these conditions outside the strait may be having a significant negative impact on the overall marine survival.

36.2. Introduction

Juvenile salmon generally enter the Strait of Georgia from April to June and many may remain and rear in the strait until the fall. The juvenile trawl surveys are designed to sample juvenile salmon throughout the Strait of Georgia during this first ocean summer and fall. In 2015 juvenile salmon were sampled during two trawl surveys (June 24-July 9 and September 16-October 6). These surveys fished standard track lines that have been fished since 1998 following the protocol in Beamish et al. (2010). In addition, additional sampling was conducted in the Discovery Islands, mainland inlets, Gulf Islands and Puget Sound. The surveys were conducted with the Canadian Coast Guard research vessel *W.E. Ricker*.

Beamish et al. (2010) demonstrated that there was a good relationship between the catch rate of juvenile Coho Salmon in the September survey and returns of adults the following year. This work indicated that brood year strength for Coho Salmon from the Strait of Georgia was determined during their first summer in the ocean and within the Strait of Georgia region. In this report we make the assumption that early marine survival is a major component of determining overall marine survival for all salmon species in the Strait of Georgia. We examine the catch rates of juvenile salmon in 2015 in comparison to catch levels from 1998-2014, the condition of the juveniles and the general oceanographic conditions in the Strait of Georgia. We use the information collected in 2015 to estimate the relative strength of return in subsequent years (return year depends on the species).

The surface water temperature (SST) in May-June 2015 was the highest in the time series since 1961 (Chrome Island, Figure 36-1). There is indication that the survival of juvenile salmon may be inversely related to SST (Friedland et al. 2003, Beamish et al. 2009, Petrosky and Schaller, 2010). However, Mueter et al. (2005) suggested that these ocean conditions may only explain a small proportion of the variability in salmon survival driven by environmental factors. Therefore, the increase in the SST during the early summer 2015 is a note of caution as we do not know the impact on the survival of juvenile salmon entering the ocean in these years.

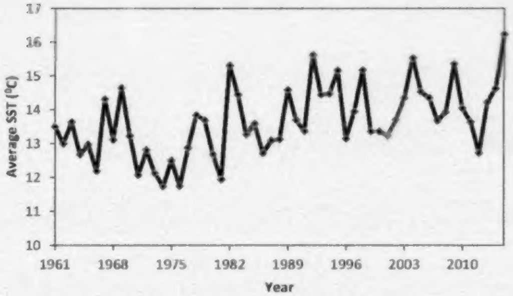

Figure 36-1. Average sea surface temperature (SST) in May and June at the Chrome Island light station, 1962-2015.

36.3. Coho Salmon

Coho Salmon generally spend one winter in the ocean, therefore, most juveniles that entered the ocean in 2015 will return to spawn in 2016. Chittendon et al. (2009) demonstrated that Coho Salmon from the Strait of Georgia remain and rear in the strait until late fall. Beamish et al. (2010) used the abundance and survival of Coho Salmon up to the annual September surveys to demonstrate that brood year strength for Coho Salmon was determined in the Strait of Georgia during the first marine summer. In 2015 the catch per unit effort (CPUE) of Coho Salmon in the September survey was the second highest observed in the time series (Figure 36-2). In addition, the average size of the juveniles was the largest observed in the 17 years of the survey. Based on the early marine index developed by Beamish et al. (2010) these conditions would suggest a **good** return of Coho Salmon in 2016. However, the poor return of Coho Salmon that entered the ocean in 2014 leaves a note of caution. If the warmer waters warmer water temperatures on the west coast of Vancouver Island during the winter of 2014/2015 (Chandler 2015) had a negative impact on the survival of these coho past their first marine, then continued warm water on the west coast during the winter of 2015/2016 could also impact the overall survival of these juveniles.

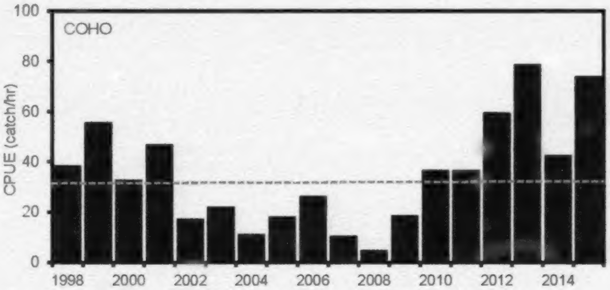

Figure 36-2. The CPUE of Coho Salmon in September trawl surveys in the Strait of Georgia 1998-2015. Red dashed line is the average catch over the time series.

36.4. Sockeye Salmon

Sockeye Salmon that entered the Strait of Georgia in 2015 were mostly progeny of the return to the Fraser River in 2013. This is the same cycle line that had the poor return in 2009 and triggered the Cohen Commission Inquiry on Fraser River Sockeye Salmon. Therefore large numbers of juveniles were not expected to be observed in 2015. The catch in 2015 was lower than 2011 but greater than our observations in 2007 (juveniles of 2009 return failure; Figure 36-3A). The average size (137.4 mm) of these fish was the largest observed for the cycle year and the second largest of all years sampled. Feeding (based on percent of empty stomachs) in 2015 was average. Therefore, except for the warming SST, the conditions within the Strait of Georgia appeared average for the juvenile Sockeye Salmon. Since this is a low cycle line, returns in 2017 are not expected to be large. The condition and numbers of juveniles observed in the Strait of Georgia would suggest that this will be consistent in 2017 with neither anomalously high or low returns for this line observed.

Harrison River Sockeye Salmon are a Fraser River stock that does not spend one winter in lakes but migrates to the ocean in the spring in which they emerge and in general have had improved production over the past few years. Information that is known about their ocean entry suggests that they enter in late July and August. During the June/July survey small numbers of these fish are captured in Howe Sound but are rarely captured in the Strait of Georgia until August or September. In September, they are the dominant stock of Sockeye Salmon within the strait representing over 95% of the Sockeye Salmon captured (Beamish et al. 2012). In September 2015 the CPUE of Sockeye Salmon in the standard survey area was very low (Figure 36-3B). The juveniles were captured in Howe Sound and mainland inlet regions that are not included in the CPUE calculation and the average size of the juveniles was above average. Overall, the catch and distribution of Sockeye Salmon in the September survey suggests average to poor returns for Harrison River Sockeye Salmon in 2017 and 2018.

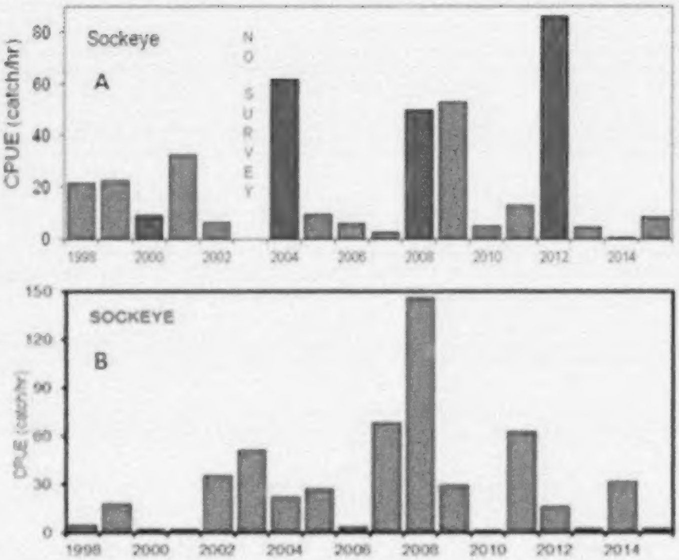

Figure 36-3. The CPUE of Sockeye Salmon in the (A) June/July and (B) September survey of the Strait of Georgia 1998-2015.

36.5. Chinook Salmon

Chinook Salmon early life history is complex with variation in life history type (ocean and stream-type, hatchery and wild), age at ocean entry and timing of ocean entry. Beamish et al. (2011) demonstrated that the catch of Chinook Salmon in the June-July surveys are a mixture of ocean and stream type fish. Neville et al. (2015) demonstrated that most of these juvenile fish present in the June-July survey either leave the strait or die before September. The CPUE of Chinook in the June-July survey was higher in 2015 than had been observed for the past few years but could still only be considered average (Figure 36-4A). The largest catches were in the southern Strait of Georgia with large numbers near Howe Sound and along the east coast of Vancouver Island. This is a shift in the distribution and may indicate a change in the stock composition from previous years (DNA results not yet available). The average size of the fish was similar to 2014 and one of largest we had observed in the time series. However, additional analysis is required to determine if the change in size is due to a shift in the proportion of ocean and stream type fish in the catch. The average CPUE, the southern shift in catch distribution and the possible shift in stock composition (ocean and stream type) is an indication that additional research on factors regulating survival during this early marine period is required.

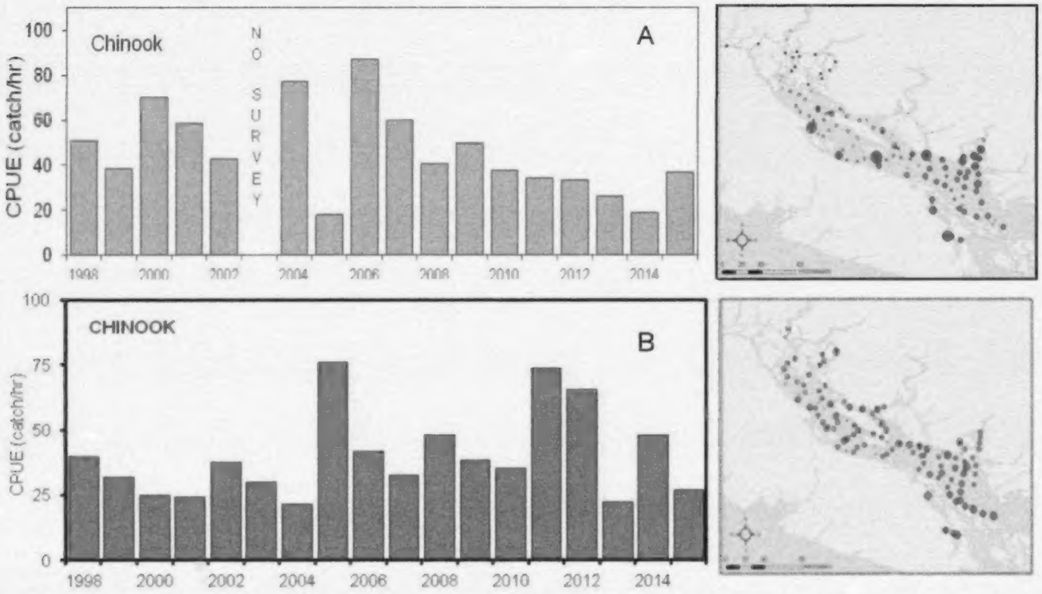

Figure 36-4. The CPUE of Chinook Salmon in the (A) June/July and (B) September survey of the Strait of Georgia 1998-2015.

In September the majority of the Chinook Salmon in the Strait of Georgia are from the South Thompson region (Beamish et al. 2011). These fish generally enter the ocean in late July and August and, similar to Harrison River Sockeye Salmon, have had improved production over recent years. In September 2015 the CPUE of Chinook Salmon was average (Figure 36-4B) but the average size of the fish was above average. There was a bi-modal distribution in the length frequency of these fish however which may indicate a change in the stock composition of the fish. They were captured throughout the survey region. There are no indicators of extremely poor conditions for these fish, however further work is required on the stock composition to determine if shifts in the ocean and stream proportions may be occurring.

36.6. Chum Salmon

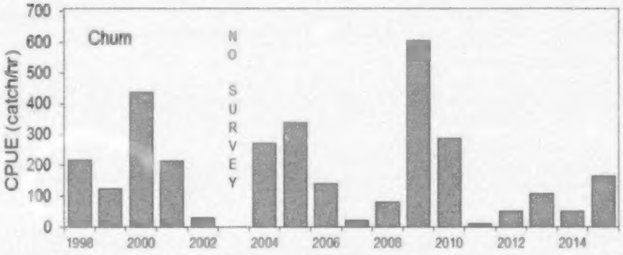

Figure 36-5. The CPUE of Chum Salmon in the June-July trawl survey in the Strait of Georgia 1998-2015.

Chum Salmon enter the ocean in the year they emerge from the gravel and are produced in numerous rivers and stream around the Strait of Georgia. In 2015 the CPUE of Chum Salmon in the June-July survey was the highest observed since 2010 (Figure 36-5). In addition, the average size of the juveniles was above average. This increase in size may be due to earlier migration of the juveniles into the marine environment. However, in addition to this, the low numbers of empty stomachs indicated good feeding conditions in the ocean. The increased CPUE of Chum Salmon and the above average size are positive indicators for adult returns in 2017 and 2018. However, it is unknown how the changes in ocean conditions may impact the overall survival of this species.

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37. TELEMETRY-BASED ESTIMATES OF EARLY MARINE SURVIVAL AND RESIDENCE TIME OF JUVENILE STEELHEAD IN THE STRAIT OF GEORGIA AND QUEEN CHARLOTTE STRAIT, 2015

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37.1. Highlights

- Early marine survival and travel times were estimated for hatchery-reared Seymour River summer steelhead smolts using internally-implanted acoustic tags.
- Two additional detection sub-arrays were deployed in the southern Discovery Islands and in Johnstone Strait in 2015.
- Survival of smolts released into the ocean near West Vancouver had three times higher survival to the northern Strait of Georgia than smolts released in the lower Seymour River, indicating that Burrard Inlet is a mortality hotspot.
- Early marine survival was highest in the central Strait of Georgia but lower in the northern Strait of Georgia to Queen Charlotte Sound, consistent with Sockeye Salmon tracked from 2004-2007 (hatchery-reared Cultus Lake smolts) and from 2010-2014 (wild two-year-old Chilko Lake smolts).
- Steelhead smolts migrated at about 1 body length per second (BL/sec) in the Strait of Georgia, but much faster to the northern end of Vancouver Island. Median travel time from release to the northern end of Vancouver Island was only 21 days.
- A new, smaller transmitter was also field tested in 2015 on the newly deployed and redesigned sub-arrays. The promising performance of the array means early marine survival can be assessed for a wider range of salmon smolts that migrate north via Johnstone Strait.

37.2. Summary

We used a large-scale acoustic telemetry array to track Seymour River (North Vancouver) summer steelhead smolts during their early marine migration. Salmon smolts (n=273; average fork length=20 cm) were selected randomly and surgically implanted with uniquely coded acoustic transmitters ("tags"). Smolts were transported via truck and released at three sites: 1) at the standard release location in West Vancouver near the DFO's Centre for Aquaculture and Environmental Research lab (WVL); 2) in the lower Seymour River (to assess survival through Burrard Inlet); and 3) upstream of the December 2014 rockslide site in the Seymour River (to assess passage success). Fish were tracked with a network of acoustic sensors positioned in the river and throughout the greater Salish Sea area, including two new dual-frequency sub-arrays in the Discovery Islands and in Johnstone Strait (Figure 37-1).

By reconstructing the movements of each individual salmon from the data recorded by the array, it was possible to estimate survival through almost 400 km of migration from release in the lower Seymour River through the Strait of Georgia (SoG), the Discovery Islands (DI),

Johnstone Strait (JS), and up to northern Queen Charlotte Strait (QCS) using the Cormack-Jolly-Seber model (CJS; Cormack 1964; Jolly 1965; Seber 1965). We compared survival of the Seymour River release group to those released near WVL, and also determined residence time (travel time) and travel rate in these key areas. None of the fish released above the rockslide were ever detected on the acoustic array.

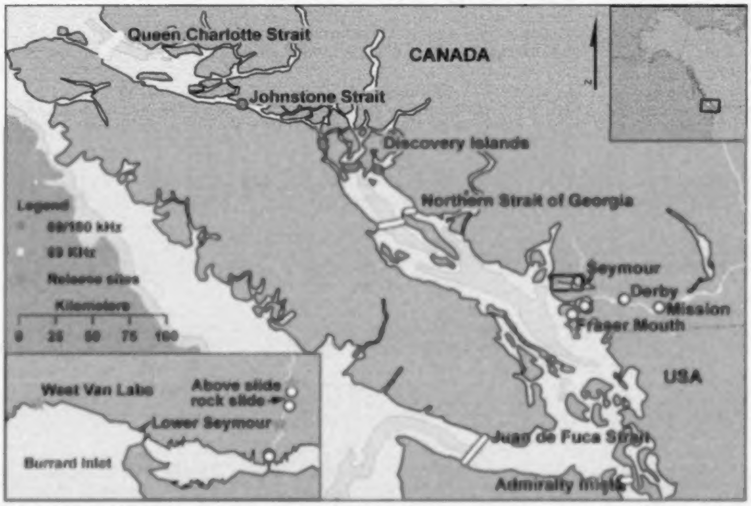

Figure 37-1. Map of the acoustic receiver array used to track juvenile Seymour River Steelhead Salmon in 2015. Yellow lines and dots represent single frequency receiver sub-arrays, while red dots and lines represent dual frequency sub-arrays deployed in 2015. Components of the array are variously managed by Kintama Research Services (Fraser River), the University of British Columbia (Seymour River; deployed for 2015 only), the Pacific Salmon Foundation (Discovery Islands and Johnstone Strait), the Northwest Fisheries Science Center (NOAA-NWFSC; Admiralty Inlet), and the Ocean Tracking Network (OTN; Juan de Fuca, Northern Strait of Georgia, Queen Charlotte Strait). The pink stars represent the release sites of acoustic tagged smolts in 2015. Isobaths (200 and 500 meter) are coloured in pale blue.

Our results from 2015 indicate that survival patterns of Seymour River summer steelhead smolts are consistent with acoustic tagged sockeye patterns: survival in the SoG and up to QCS was similar between the two species, and daily survival rates were highest in the SoG and then decreased between the northern Strait of Georgia sub-array (NSOG) and the QCS sub-array. Additional sub-arrays deployed in the Discovery Islands and Johnstone Strait allowed us to estimate survival in the northernmost section of the Strait of Georgia (between NSOG and the southern Discovery Islands), and through the Discovery Islands region. Survival in these two areas was higher than the area between the JS and QCS sub-arrays. Travel times indicate that smolts migrate very rapidly out of the SoG and Queen Charlotte Strait likely due to their large body size. Less than one month after ocean entry, most smolts reached the central B.C. coast.

37.3. Early Migration Survival Estimates

Survival of WVL-released Seymour steelhead to the NSOG sub-array was 65% (SE=5%), while survival of the Seymour River released fish was only 21% (SE=6%; Figure 37-2; Figure 37-3). This 3-fold difference in survival indicates that mortality in the lower Seymour River and particularly in Burrard Inlet, an additional distance of only ~20 km, significantly impacts survival of migrating smolts. None of the fish released above the rock slide were ever detected downstream indicating that the rock slide may prevent juvenile salmon from migrating downstream.

Although predation was not directly observed in our study, piscivorous birds are concentrated in the area near the mouth of the Seymour River (Butler et al. 2015). This likely accounts for some of the mortality that occurred in our study and an earlier study by Balfry et al. (2011) which found similar declines in survival in Burrard Inlet and prompted the hatchery to continue to release fish at the WVL site instead of in the lower Seymour River.

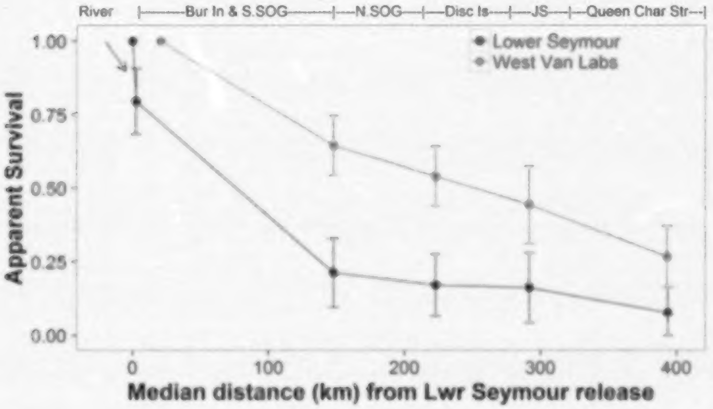

Figure 37-2. Cumulative survival of Seymour River steelhead smolts transported and released in the lower Seymour River and in West Vancouver near the DFO lab. Bur In & S.SOG= Burrard Inlet and central Strait of Georgia, N.SOG=northern Strait of Georgia, Disc Is= Discovery Islands, JS=Johnstone Strait ; Smolts were implanted with 7 mm diameter VEMCO transmitters. Error bars are 95% confidence intervals.

Survival in the migration segments north of the NSOG subarray were similar between the two release groups (Figure 1-3). Thus the 3-fold difference in survival observed to NSOG was maintained to the final detection site (QCS) at the northern end of Vancouver Island (WVL release group=27%, SE=5% vs. Seymour River release group=8%, SE=4%) because of some losses in the lower Seymour River and high mortality in Burrard Inlet.

Survival of the WVL-release group to the NSOG sub-array was similar to the average survival of two-year-old Chilko Lake sockeye smolts from the mouth of the Fraser River to the NSOG sub-array which ranged between 38-82% from 2010-2014 (Clark et al. 2016), and for hatchery reared Cultus Lake sockeye smolts which ranged between 38-92% from 2004-2007 (Rechisky et al. 2015, Welch et al. 2009).

Survival from NSOG to QCS was 41% for WVL-released fish and 37% for Seymour River released fish, similar to sockeye (on average 1/3 of Chilko sockeye and 1/2 of Cultus Lake sockeye survived the same segment). Within this area, mortality was higher in Queen Charlotte Strait (Figure 37-3).

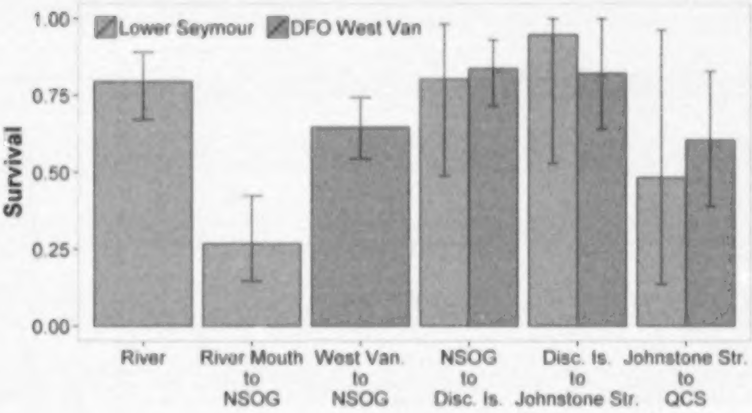

Figure 37-3. Segment survival of Seymour River steelhead smolts transported and released in the lower Seymour River and in West Vancouver near the DFO lab. NSOG=northern Strait of Georgia, Disc. Is.=Discovery Islands, QCS=Queen Charlotte Strait. Error bars are 95% confidence intervals.

37.4. Daily Survival Rates

Daily survival rate of WVL-released smolts to the NSOG sub-array was somewhat higher than daily survival rate in the northern area between NSOG and QCS, consistent with results previously obtained for sockeye (Figure 37-4). Thus, with the exception of 2006, survival rate in the SoG was generally higher than the area to the north.

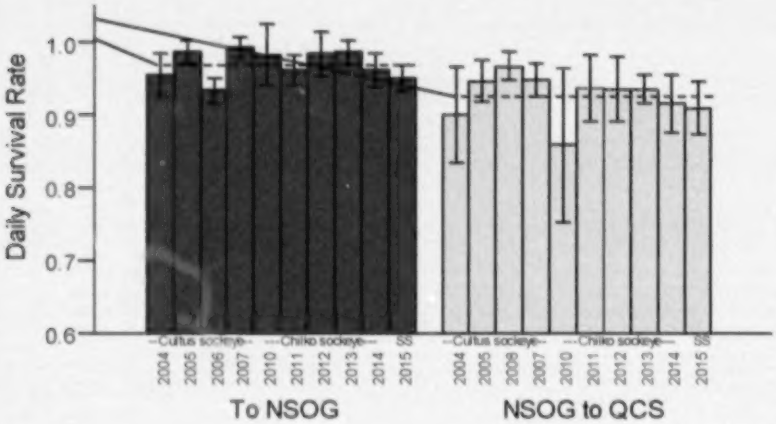

Figure 37-4. Daily survival rates for Cultus Lake sockeye (2004-2007), Chilko Lake sockeye (2010-2014), and WVL-released Seymour River steelhead smolts (SS; 2015). The dashed line represents the mean daily survival rate for all years. NSOG=northern Strait of Georgia, QCS=Queen Charlotte Strait. Error bars are 95% confidence intervals.

37.5. Residence Time in the Strait of Georgia and Queen Charlotte Strait

The steelhead smolts moved quickly through all habitats but residence in the SoG was longer than in Johnstone Strait and Queen Charlotte Strait. WVL-released smolts took approximately 16 days to reach the Discovery Islands (~200 km), two days from the Discovery Islands sub-array to the Johnstone Strait sub-array (~70 km), and only three days to reach the QCS sub-array (102 km; Figure 37-5). Similar to acoustic tagged sockeye smolts, the average travel rate was one body length/second.

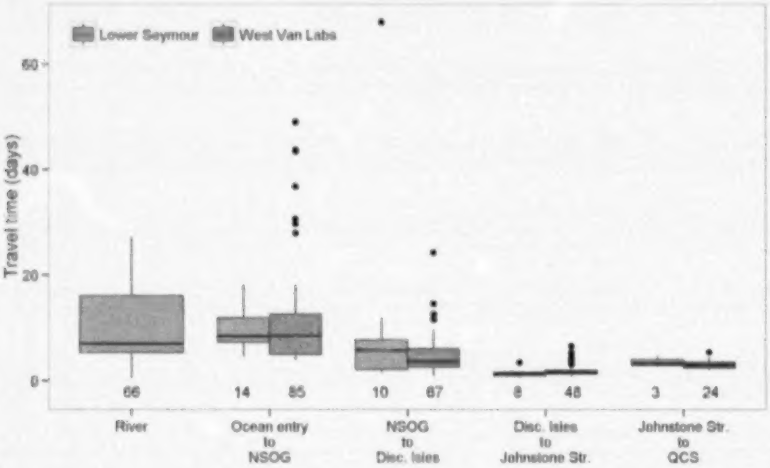

Figure 37-5. Boxplots of travel time for Seymour River steelhead smolts transported and released in the lower Seymour River or in West Vancouver near the DFO lab. Numbers along the bottom are the sample size. NSOG=northern Strait of Georgia, Disc. Isles=Discovery Islands, QCS=Queen Charlotte Strait.

37.6. Dual Frequency Array Performance

In 2015, dual frequency acoustic receivers were deployed in the Discovery Islands and in Johnstone Strait. The geometry of these arrays was redesigned (i.e. they differ from existing POST/OTN arrays) to maximize the detection rate of a new, smaller transmitter (VEMCO model V4-1H, 180 kHz). We double tagged Seymour River summer steelhead with a high powered transmitter (V9-1H, 69 kHz) and a V4 transmitter and found that the detection rate of the smaller transmitter (74%) was acceptable for estimating survival using Cormack-Jolly-Seber models. The promising performance means early marine survival can be assessed for a wider range of salmon smolts that migrate north via Johnstone Strait.

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38. FRASER RIVER SOCKEYE: ABUNDANCE AND PRODUCTIVITY TRENDS AND FORECASTS

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38.1. Highlights

- In recent years (2010-2015 return years), productivity has varied across the 19 Fraser Sockeye stocks with stock-recruitment data. Marine and freshwater factors contribute to these differences.
- Chilko is the only stock where total survival can be partitioned into freshwater and marine over a long time series. In the past decade, this stock has generally exhibited above average freshwater survival and below average marine survival.
- Fraser Sockeye returns in 2016 (2.3 million at the 50% probability level) are expected to be below the cycle average (3.9 million), due to the very low brood year escapements for many stocks in 2012.
- The warm "Blob" that has broadly covered the Northeast Pacific Ocean from the second half of 2013 to present, is characterized by water temperatures of 3 °C above average, extending down to 100 meters in depth. Given the inconsistent productivity responses across Fraser Sockeye stocks in 2015, it is unclear how productivity for the 2016 returns will be affected (i.e. whether returns will fall above or below the 50% probability level forecasts).

38.2. Summary

Most Fraser Sockeye Salmon return to freshwater to spawn as four year old fish, after generally spending their first two winters in freshwater, and their last two winters in the ocean. After their second winter in freshwater, Fraser Sockeye smolts leave their rearing lakes and migrate down the Fraser River to the Strait of Georgia. In the Strait of Georgia, they migrate north (Preikshot et al. 2012) and exit this system via the Johnstone Strait. Fraser Sockeye juveniles continue their northward migration along the continental shelf, move into the Northeast Pacific Ocean in their first winter at sea (Tucker et al. 2009), and then spend one more winter in the marine environment before they return to their natal spawning grounds as adults.

Total Fraser Sockeye adult returns have historically varied (Figure 38-1A) due to the four-year pattern of abundances (cyclic dominance) exhibited by some of the larger stocks, and variability in annual productivity (returns-per-spawner) (Figure 38-1B) and spawning escapement. After reaching a peak in the early 1990s, returns decreased to a record low in 2009 due to declines in stock productivities. Although from 2010 to 2014, productivity, and consequently returns have increased, 2015 productivity and returns were again poor for the total aggregate. The total Fraser Sockeye return and productivity trends largely represent stocks that comprise the greatest proportion of total Fraser Sockeye abundance, namely Summer Run stocks (based on return timing of adults to their spawning grounds) such as Chilko and Quesnel.

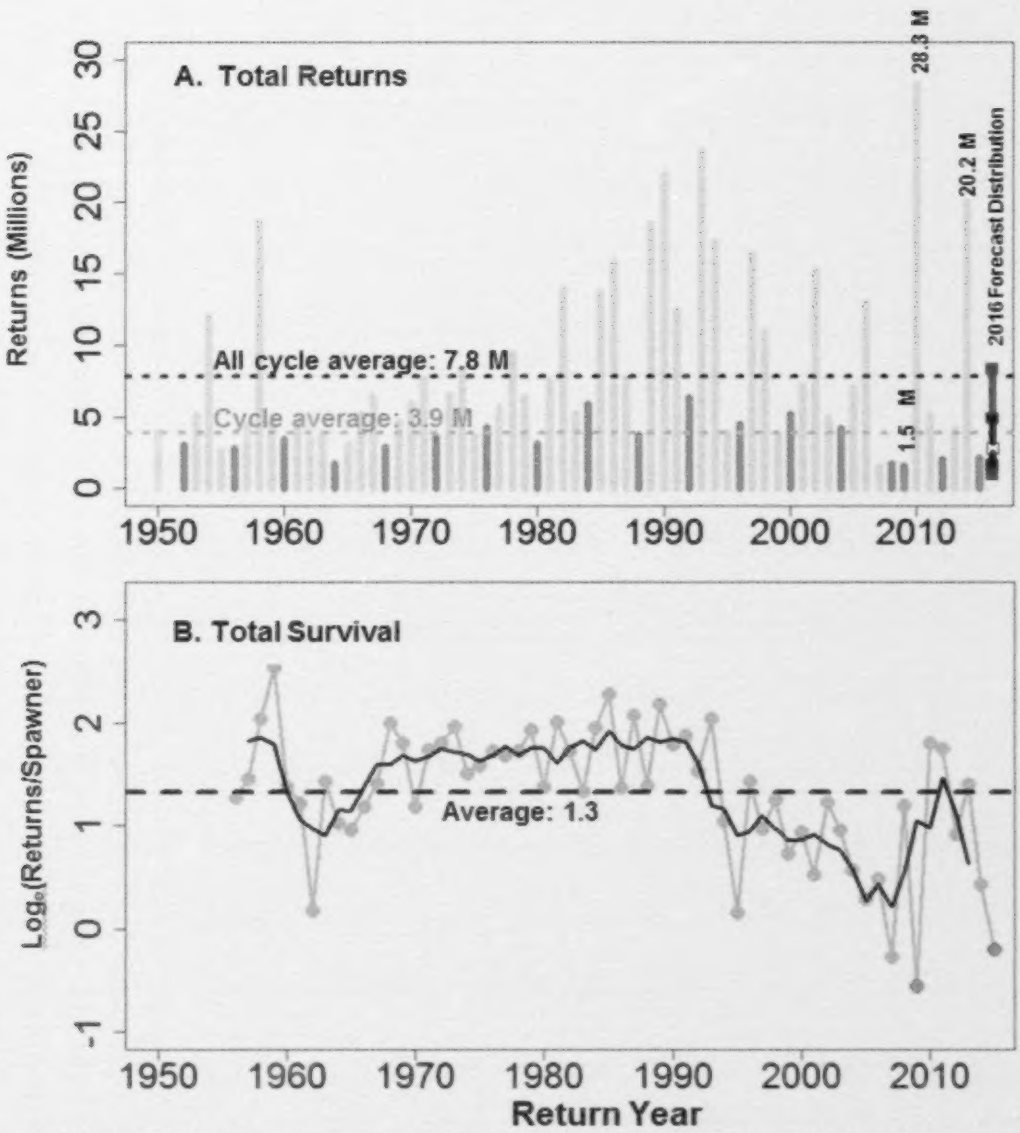
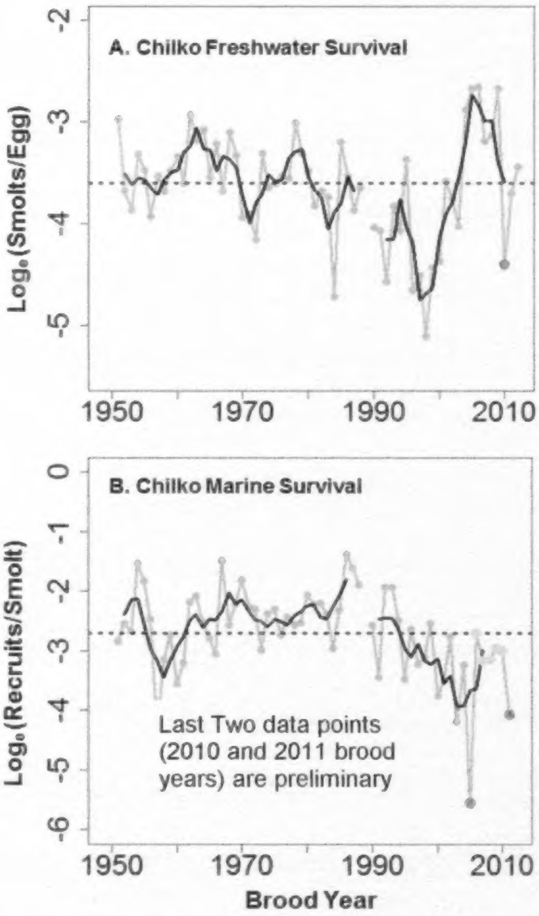


Figure 38-1. A) Total Fraser Sockeye annual returns (dark blue vertical bars for the 2016 cycle and light blue vertical bars for the three other cycles). Recent returns from 2012 to 2014 are preliminary, and 2015 is an in-season estimate only. For 2016, the pre-season return forecast is represented by the last multi-coloured vertical bar: the white square is the 50% probability level forecast (2.3 M), the range of the black bars represent the 25% and 75% probability levels (1.3 M to 4.2 M), and the range of the blue bars represent the 10% and 90% probability levels (800K to 8.1 M). B) Total Fraser Sockeye productivity (log$_e$ (returns/total spawner)) up to the 2015 return year. The light grey filled circles and lines present annual productivity and the black line presents the smoothed four year running average. For both figures, the blue dashed line is the time series average. The first red vertical bar in A (or filled circles in B) represents the 2009 returns (low productivity), and the second vertical bars in A (or filled circles in B) represents the 2015 returns (low productivity for the Fraser Sockeye aggregate).

Chilko is the only Fraser Sockeye stock with a long and complete time series of smolt data (counted through an enumeration weir located at the outlet of Chilko Lake), which can be used with this stock's escapement and return data to partition total survival into freshwater and 'marine' components ('marine' survival includes their migration downstream from the counting weir to the Strait of Georgia, and their entire marine residence period). Freshwater survival has generally improved in recent years (Figure 38-2A). 'Marine' survival data for Chilko is similar to the aggregated Fraser Sockeye survival trend (Figure 38-2B and Figure 38-1B). Chilko exhibited 'marine' survival declines in the 1990's, which culminated in the lowest survival on record in the 2005 brood year (2009 return year). Although 'marine' survival has improved in recent years (with the exception of last year's 2011 brood year, which was poor), it has remained generally below average.

Across the individual Fraser Sockeye stocks, however, there has been considerable variability in productivity (recruits-per-spawner) (Figure 38-3). Although most stocks, such as Chilko and Stellako have exhibited declining trends in the 1990's, some stocks, such as Late Shuswap, have not exhibited any systematic trends, and one stock in particular (Harrison Sockeye) has increased in productivity during this period (Figure 38-3). The common feature amongst all stocks is that productivity for the 2005 brood year was below average, and in many cases was the lowest on record, and productivity in recent years has varied across stocks (Figure 38-3).

To capture inter-annual random (stochastic) uncertainty largely attributed to Fraser Sockeye productivity, return forecasts are presented as standardized cumulative probabilities (10%, 25%, 50%, 75%, and 90%), using Bayesian statistics, rather than as single deterministic point estimates (Grant et al. 2010). At the 25% probability level, for example, there is a one in four chance the actual return will fall at or below the specified return prediction, given the historical data.


A. Chilko Freshwater Survival

B. Chilko Marine Survival

Last Two data points (2010 and 2011 brood years) are preliminary

Figure 38-2. A) Chilko River Sockeye freshwater survival (log$_e$ smolts-per-egg) and B) 'marine' (log$_e$ recruits-per-smolt) annual survival. The filled grey circles and grey lines are annual values and the black line is the smoothed four-year running average survival. Freshwater survival has generally increased in the past decade, with the notable exception of 2010 (red filled circle in A), when poor survival was associated with density-dependent factors caused by the large escapements in this brood year. Marine survival has generally been below average for the past decade, and particularly low in the 2005 and last year's 2011 brood year (two red filled circles in B). Note: Chilko 'marine' survival includes a freshwater period during their downstream migration as smolts from the outlet of Chilko Lake to the Strait of Georgia, and their entire marine residence period. The horizontal dashed line indicates average survival.

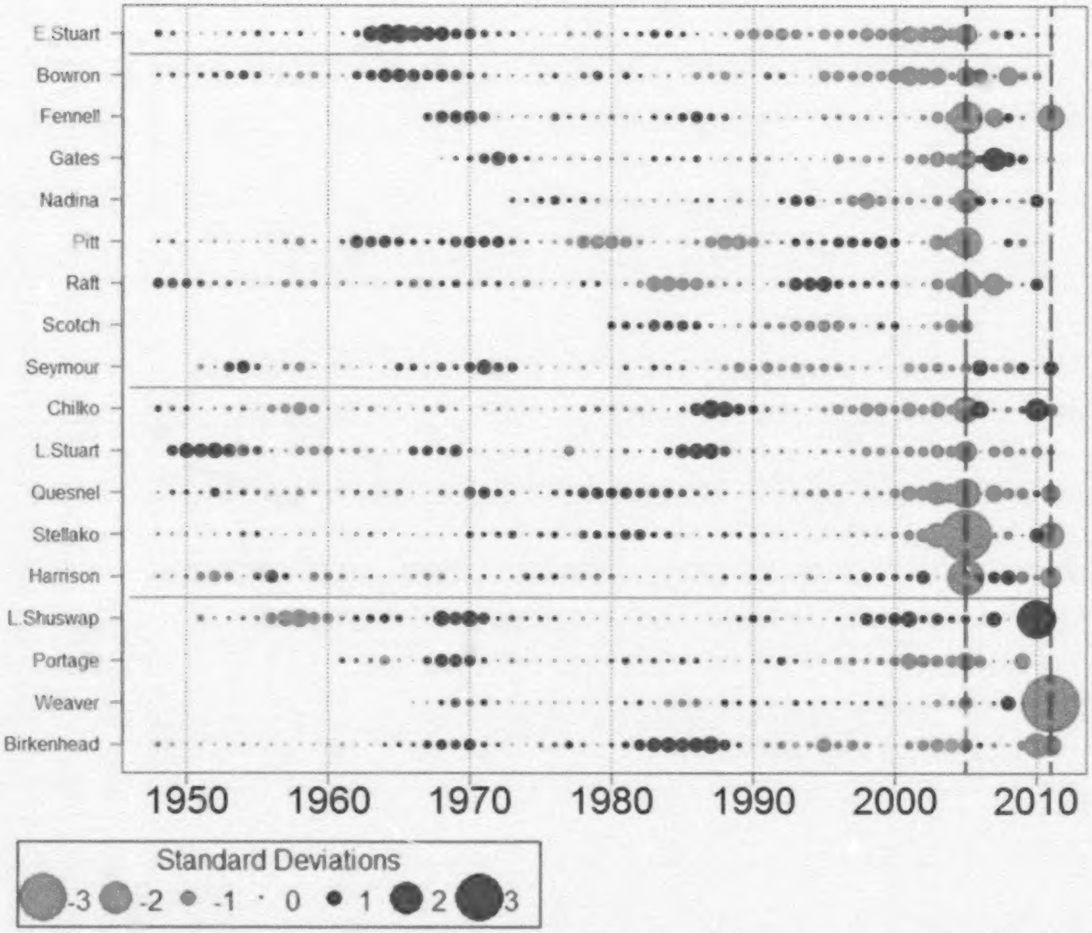


Figure 38-3. Fraser Sockeye productivity (standardized z-scores of Ricker model residuals for all stocks except Scotch, Seymour and Late Shuswap, which are Larkin residuals) up to the 2011 brood year (2015 return year). For the 2011 brood year (2015 return year), only very preliminary in-season four year old returns were used as post-season four year old returns were not available and five year old returns will not be available until 2016. In this 2011 brood year, freshwater and marine factors contribute to the observed productivities. Red filled circles indicate below average productivity and blue filled circles indicate above average productivity. The smallest circles represent average annual productivity and the larger the circle, the greater the deviation from average. Note that for Portage and Bowron productivity data were not available for these stocks in 2011 at the time of this publication.

The 2016 return forecast indicates a one in four chance (25% probability) the total Fraser Sockeye return will be at or below 1.3 million and a three in four chance (75% probability) it will be at or below 4.2 million, assuming productivity is similar to past observations. The mid-point of this distribution (50% probability) is 2.3 million (there exists a one in two chance the return will be at or below this value), which falls below the cycle average of 3.9 million (DFO 2016a (in press)).

Similar to the previous year's forecast (DFO 2015a, 2015b), a supplement Canadian Science Advisory Secretariat paper is being prepared as part of the 2016 forecast process. This supplement provides additional information on the condition and abundance of various stocks from the 2012 brood year escapement through to 2015 jack returns.

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39. SYNTHETIC INDICATORS FOR THE STRAIT OF GEORGIA MARINE ECOSYSTEM

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39.1. Highlights

- Three physical variables have significant explanatory power to identify shifts in ecosystem conditions in the Strait of Georgia (as defined over the period 1971-2007).
- Ecosystem conditions, as represented by these three proxy variables, differed in 2013-2015 from those in 2007-2012.
- 2015 clustered with 2013 and 2014, but was the weakest grouping of any year in the time series.

39.2. Background

Table 39-1. The suite of natural and human driver, pressure, state and impact variables for the Strait of Georgia examined by Perry and Masson (2013) for the period 1970-2010, to identify ecosystem indicators.

	Drivers & Pressures	**States & Impacts**
Natural	Northern Oscillation Index (NOI; annual) Oceanic Niño Index (ONI; annual) Pacific Decadal Oscillation (PDO; annual) North Pacific Gyre Oscillation (NPGO; annual) Wind speed (Vancouver airport; annual) Air temperature (Vancouver airport; annual mean) Precipitation (Vancouver airport; annual sum) Sea surface temperature (SST: Entrance Is., annual) Sea surface salinity (SSS; Entrance Is., annual) Fraser River flow (volume, annual) pH (annual modal values)	Spring phytoplankton bloom start date (modelled) Sockeye salmon marine survival (Chilko Lake) Herring (number at age 3) Herring (spawning biomass) Sockeye salmon (returns to Fraser River) Pink salmon (escapement, excluding Fraser River) Chum salmon (returns to Fraser River) Harbour seals (annual number) Killer whales (residents, annual number) Seabirds – demersal feeding (Christmas Bird Count) Seabirds – pelagic feeding (Christmas Bird Count)
Human	Chinook (number of hatchery releases) Coho (number of hatchery releases) Recreational fishing effort Human population (of Regional Districts around the Strait)	Herring (commercial catch) Flatfish (commercial catch) Pacific cod (commercial catch) Lingcod (commercial catch) Pacific hake (commercial catch) Dogfish (commercial catch) Total commercial fish catch Total pelagic fish catch Total demersal fish catch Chinook salmon recreational catch Coho salmon recreational catch

This project involves the identification and development of synthetic ecosystem-scale indicators of changes in the Strait of Georgia. In a previous analysis, Perry and Masson (2013) used redundancy analysis to explore the relationships between 15 natural and human driver and pressure (explanatory) variables with 22 state and impact (response) variables for the Strait of Georgia from 1970-2010 (Table 39-1). They identified six variables which had significant explanatory power to identify shifts in the broad suite of ecosystem response variables in the Strait. These six variables were sea surface temperature (SST), wind speed, North Pacific Gyre Oscillation (NPGO), human population, recreational fishing effort, and the number of Chinook Salmon released from hatcheries in the Strait. The present analysis repeated the previous analysis using the three natural variables (SST at Entrance Island, wind speed at Vancouver airport (YVR), and the annual mean NPGO Index) to see if they also had high explanatory power for changes in ecosystem conditions over the period 1970-2010. The present analysis also updated these time series as a proxy for potential ecosystem changes from 2010 to 2015.

Redundancy analysis applied to these three physical variables, over the period 1970-2010, produced very similar results, in terms of the timing of ecosystem changes, to that derived from the original analyses by Perry and Masson (2013) using the six natural and human variables (Figure 39-1). The conclusion is that these three natural variables can be used to adequately describe changes in the overall conditions of a broad suite of natural and human state and impact (response) variables for the Strait of Georgia.

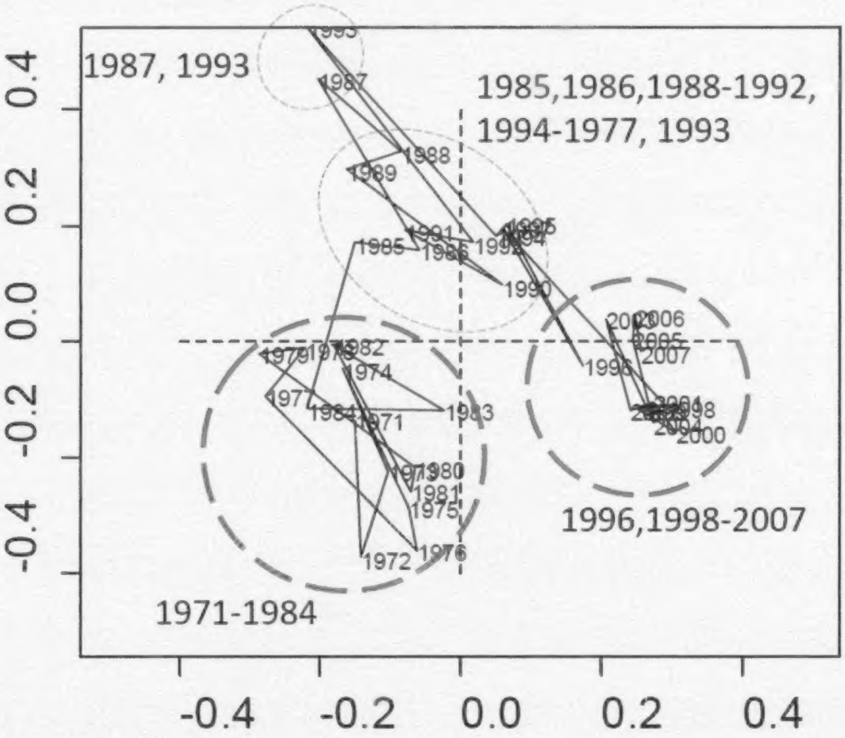

Figure 39-1. Redundancy axes for the three natural variables (sea surface temperature, wind speed, NPGO index) for 1970-2010 for the Strait of Georgia. Axis 1 (X-axis) accounts for 61% of the total variance; axis 2 (Y-axis) accounts for 6% of the total variance. The patterns of year groupings are consistent with those derived from the six variables used by Perry and Masson (2013).

The full time series of annual values for these three natural variables, extending from 1970 and updated to 2015, is presented in Figure 39-3. These variables were standardized (0 mean, unit variance) and a chronological clustering technique was used to group adjacent years which had similar values (this method keeps years in their sequential order). A randomization test indicated that 7 clusters were statistically significant (Figure 39-2), with 2015 grouping (very) weakly with 2013 and 2014. Reference to Figure 39-3 shows that these most recent three years had strongly increasing sea surface temperature, neutral wind speeds, but strongly decreasing NPGO.

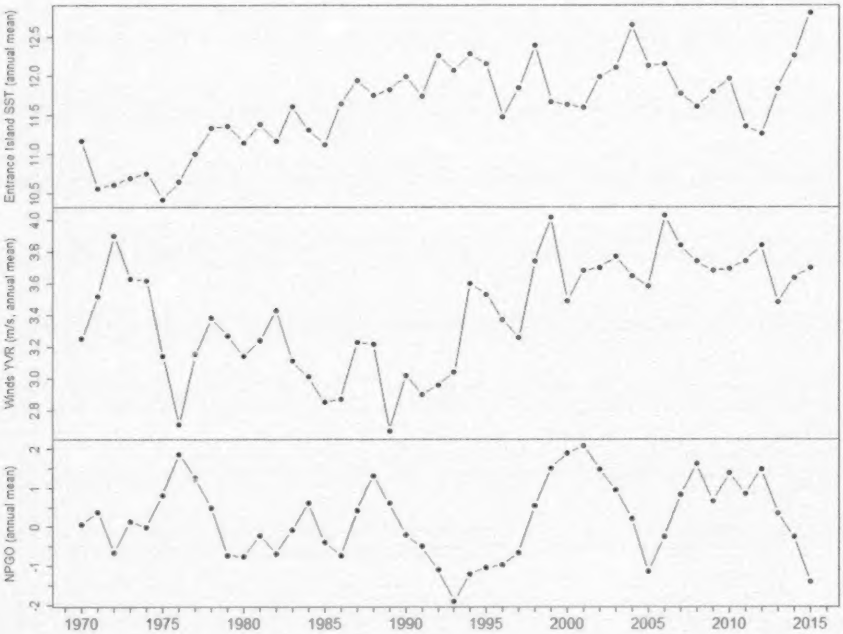

Figure 39-3. Time series of the three key explanatory variables, as annual means from 1970 to 2015. These key variables are sea surface temperature at Entrance Island (top), wind speed at Vancouver airport (YVR) (middle), and the North Pacific Gyre Oscillation Index (NPGO) (bottom).

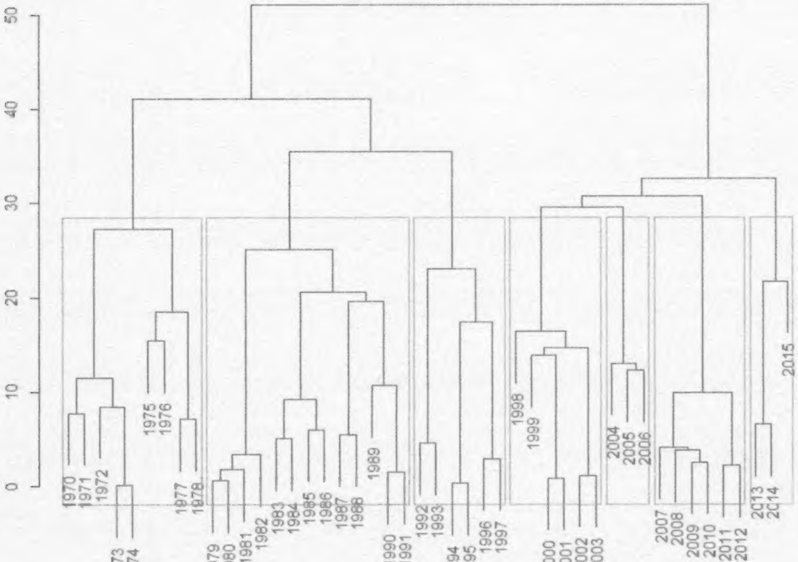

Figure 39-2. Chronological clustering of years (1970-2015), using the three key natural explanatory variables (NPGO, YVR wind, Entrance Island SST). Red boxes identify significant clusters based on a randomisation technique.

39.3. Conclusions

- Six variables (three natural and three human) were identified by Perry and Masson (2013) as having significant explanatory power to identify shifts in ecosystem conditions in the Strait of Georgia, for the period 1971-2007.
- The three natural drivers alone have significant explanatory power to identify shifts in ecosystem state in the Strait of Georgia.
- These natural drivers predict changes in ecosystem conditions in years that are consistent with general understanding (i.e. the timing of regime shifts in this system);
- Ecosystem conditions differed during 2013-2015 from those in 2007-2012.
- 2015 clustered with 2013 and 2014, but was the weakest grouping of any year in the time series.

39.4. References

Perry, R.I. and Masson, D. 2013. An integrated analysis of the marine social-ecological system of the Strait of Georgia, Canada, over the past four decades, and development of a regime shift index. Progress in Oceanography 115: 14-27.

40. COASTAL OCEAN RESEARCH INSTITUTE AND OCEAN HEALTH REPORTING

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40.1. Highlights

- The Coastal Ocean Research Institute housed at the Vancouver Aquarium Marine Science Centre has launched a Coastal Ocean Health Initiative which will focus on reporting on indicators of ocean health.
- CORI is producing a pilot ocean health report in 2016 for Howe Sound and gathered feedback at the State of the Pacific Ocean meeting, March 2, 2016, on reporting formats and approaches.
- CORI is working with a variety of partners on the ocean health reporting initiative and is aiming to produce a B.C. report in 2017.

40.2. Mission and Vision

The mission of the Coastal Ocean Research Institute (CORI) is to produce and communicate scientific knowledge, evidence, and understanding in service of:

1. protecting coastal ocean life and habitats, ensuring they remain healthy for generations to come;
2. informing responsible economic activity; and,
3. safeguarding communities.

CORI is set up as an independent research institute, housed at Vancouver Aquarium Marine Science Centre. It is intended to be a place where governments, First Nations, researchers, businesses, donors and non-profit organizations can work together on pressing issues facing our coast.

A key strength and foundation of CORI is communicating science in a clear, understandable, and engaging manner. CORI benefits from the Vancouver Aquarium's long standing reputation, expertise, and set of platforms for engaging people. This includes over 1.1 million on-site visitors, over 20 million digital visitors, more than 600 partners, over 60,000 citizens participating in shoreline clean ups and citizen science, and over 80,000 students a year. Last year, stories about CORI science generated over 2 billion media impressions around the world.

40.3. CORI Programs

There are four current program areas. The Howe Sound Research Program, focusing on coastal ecology and the relationship to climate factors, is led by Dr. Jeff Marliave and Jessica Schultz. The Marine Mammal Research Program, led by Dr. Lance Barrett-Lennard, largely focuses on cetaceans, including the world's longest continuous study of killer whales, and uses methods of photo identification, acoustic and DNA analysis and, more recently, photogrammetry. The Ocean Pollution Research Program, led by Dr. Peter Ross, researches the sources and consequences of ocean pollution, including a range of contaminants, micro-plastics and hydrocarbons.

The Coastal Ocean Health Initiative was launched in late 2015 and is focused on bringing together the best available knowledge on the state of British Columbia's coastal ocean and presenting it in a way that is clear, engaging, and provides insight into overall coastal ocean health. The initiative is being led by Karin Bodtker, who will work in collaboration with First Nations, governments, NGOs, industry, educational institutions, citizen scientists, and others. The reports will include themes representing ecological, socioeconomic, cultural, and governance subjects. Reports will provide decision-makers, stakeholders, and the public with key insights into coastal ocean ecosystems including status, trends, drivers, risks, and emerging issues.

While the initial geographic scope for this initiative is British Columbia, some reports will focus on sub regions. Reports will combine narrative and data with the intent of making scientific information more accessible, allowing people to make informed decisions and take appropriate action. Emerging and current issues will help to determine the range of topics chosen to highlight in each report.

40.4. Pilot Coastal Ocean Health Report for Howe Sound in 2016

Drawing on an ecosystem-based management framework, we identified seven reporting themes that together represent a holistic view of coastal ocean ecosystem (Table 40-1). We are compiling information to produce a pilot report in 2016 which focuses on Howe Sound in the Strait of Georgia. Contributors and collaborators in this effort to date include government and citizen scientists, local representatives, engaged citizens, the Squamish Nation, and the David Suzuki Foundation.

Table 40-1. Coastal Ocean Health reporting themes and a selection of example topics for Howe Sound.

Reporting theme	Howe Sound example topics
Sense of Place and Wellbeing	Spotlights on citizen science
Stewardship and Governance	Marine Protected Areas
Coastal Development and Livelihoods	Tenure applications & purpose
Seafood	Prawn fisheries
Oceanography and Climate Change	District of Squamish and sea level rise
Species and Habitats	Sea star wasting
Clean water	Water quality; effluent at pulp mills

40.5. Participant feedback at State of Pacific Ocean Meeting, March 2, 2016

At the State of the Pacific Ocean Meeting, March 2, 2016, we requested feedback from meeting participants on a number of questions. While we report the results here, we understand the audience was not representative of any particular larger population and make no inferences about the feedback provided.

Question: Are there existing datasets for Howe Sound that would be useful in informing the themes?

Responses included:

- "B.C. Cetacean Sightings Network"
- "RCA compliance"
- "Juvenile salmon tracking"
- "Sponge locations"
- "Bathymetry"
- "Water level"
- "Weather station data"
- "Streamflow"
- "Herring spawn"

We presented four example reports illustrating a range of formats and approaches to indicator reporting (Table 40-2) and gathered feedback from meeting participants about their preferences (Table 40-3).

Table 40-2. Example indicator reports with illustrative differences in format and approach.

Report name	Format	Approach
Chesapeake Bay Foundation, State of the Bay	Status in two paragraphs, no data, few graphs presented, downloadable pdf	Score and change in score reported; scoring explained on back page.
Puget Sound Vital Signs	Two pages per indicator, status shown in chart or map, short explanation text, graphics widely used	2020 target, progress signal describing trend, no score
Health of the Salish Sea Ecosystem Report	Web-based delivery, short narrative based on simple questions, detailed data available through links	Description of trend, no target, no score
NOAA – Arctic Report Card	Web-based, content and look very similar to extended scientific abstract, data are illustrated with charts, maps	Description of status, trend, without commentary or interpretation, no target, no score

Table 40-3. Preferences on visual appeal and recommended approach based on presented example reports.

Example Report	Q1. Which is most visually appealing? (percent, n = 39)	Q2. Which approach do you recommend? (percent, n = 40)
Chesapeake Bay Foundation, State of the Bay	13	12.5
Puget Sound Vital Signs	44	25
Health of the Salish Sea Ecosystem Report	23	50
NOAA – Arctic Report Card	20	12.5

Lastly, we asked for comments on visual presentation and on recommended format for reporting. Comments on visual presentation included:

“Interactive”
“Targets specify exactly how you will fail”
“Simplicity”
“Drill down ability”
“Simplicity”
“Interactive”
“Maps”
“Concise”
“Layered info, scalable data”
“Images and figures”
“Simple”
“Easy to read graphics”.

Comments on recommended format included:
“Think about shifting baselines”
“Targets are difficult to determine”
“Narrative is engaging”
“Scores are easy for the public to get”
“Great approach”
“No target, no score”
"Open Data"
“Qualitative research”
“How to reach decision makers”
“Targets are tricky”
“Look at gulf of Maine ESIP”
“Keep public documentation simple, but provide resources where folks can get more scientific detail on how scores/trends were derived”
“Targets are relative”
“What about risks?”
“Consider target audience(s)”
“Simplicity for sustainability”
“Plan for future conditions”
“Scores that combine apple and oranges are unconvincing”
“Easy to interpret trend line helps people understand past, present, future.”
“Transboundary/Salish Sea with us partners”
“Reporting on state of the research is part

Please contact the authors with any further questions or comments.

41. TRENDS IN CANADIAN MARINE RESEARCH: CURRENT STATE AND INFORMATION GAPS

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41.1. Highlights

- A metadata repository on Canadian marine research is being compiled as part of the Ocean Canada Partnership.
- Preliminary results show a prevalence of single-species research throughout Canada, though more multi-species and ecosystem-based research is available for the Pacific Ocean.
- An integrated metadata repository aids interdisciplinary research and highlights general trends and data gaps.

41.2. Background

Comprehensive integration of available information on ocean resources has become more necessary as research and governance address broader ecological, spatial and temporal dynamics and how these affect social-ecological systems at various scales (Arkema et al. 2006, Díaz et al. 2015) (Figure 41-1). Providing information is a prerequisite of adaptive governance (Dietz et al. 2003), and requires varied forms of data from multiple disciplines to map the effects of natural changes (e.g. biophysical) and human actions (e.g. overfishing) on ocean environments. This has been further and formally expressed within the UN Convention on Biological Diversity (CBD), whose goals aim to reduce pressures on natural systems (Tittensor et al. 2014), but also to encourage sustainable industries and enhance the benefits derived from ecosystem services (UNEP 2010). These objectives are clearly aligned with Canada's national legislation and marine policy goals.

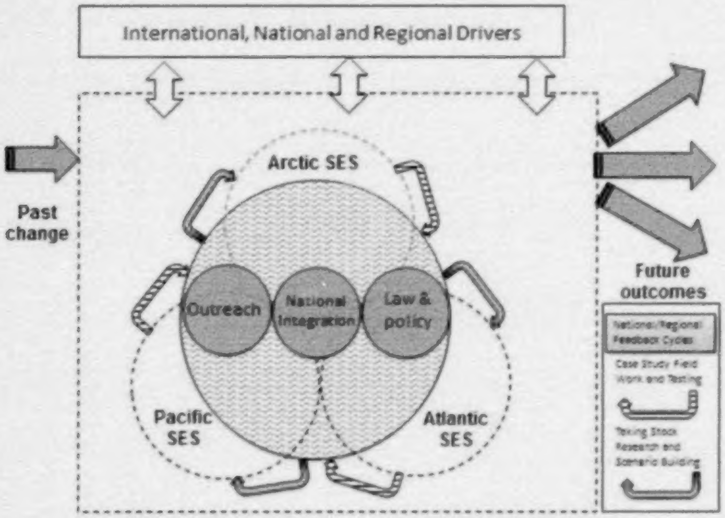
International, National and Regional Drivers
Past change
Arctic SES
Outreach
National Integration
Law & policy
Pacific SES
Atlantic SES
Future outcomes
National/Regional Feedback Cycles
Case Study Field Work and Testing
Taking Stock Research and Scenario Building

Figure 41-1. Ocean Canada Partnership goals and context diagram. Pacific, Arctic, and Atlantic social-ecological systems (SES) are analyzed in terms of specific human and natural drivers and outcomes. The metadata repository is a key component used to inform analyses at various scales.

Canadian marine research is relatively comprehensive and systematic compared to many other regions, with many research networks including government agencies, universities and independent research institutions, and non-government organizations (NGOs). Such a diversified set of networks has produced data on a range of topics, yet a drawback of this inherently de-centralized research is that data and information are available at different locations, scales, and in various formats, potentially limiting their accessibility for interdisciplinary analyses. Therefore, a central aim of the Ocean Canada Partnership—a SSHRC-funded initiative involving over 15 formal partner institutions throughout the country—is to compile a metadata repository of available marine research in Canada. This is a first step towards scenario analyses involving local and regional scales (Figure 41-1), but also allows for interesting analyses of ongoing trends and current data (and/or accessibility) gaps.

41.3. Preliminary results

Overarching trends and challenges in Canadian marine research have been identified by experts in the field (Council of Canadian Academies 2013), and indeed are supported by the metadata presented here. Importantly, key information gaps—including temporal, spatial, or thematic—have strong implications for subsequent research and policy, and require specific strategies for improvement.

The metadata repository currently includes almost 1,100 records including the Arctic (n=76), Atlantic (n=476), and Pacific (n=430) Oceans, as well as national-level assessments (n=83). Canadian ocean research has steadily increased throughout the 1980s-2000s (Figure 41-2). Though there is a strong prevalence of data and reports dealing with single species, there is a growing number of multi-species and ecosystem-based research available. Nevertheless, single-species assessments (particularly related to fisheries) generate the majority of available data, particularly in the Atlantic region. The Pacific region shows a somewhat more balanced set of assessment themes, with the Arctic region significantly underrepresented in terms of available assessments (Figure 41-3).

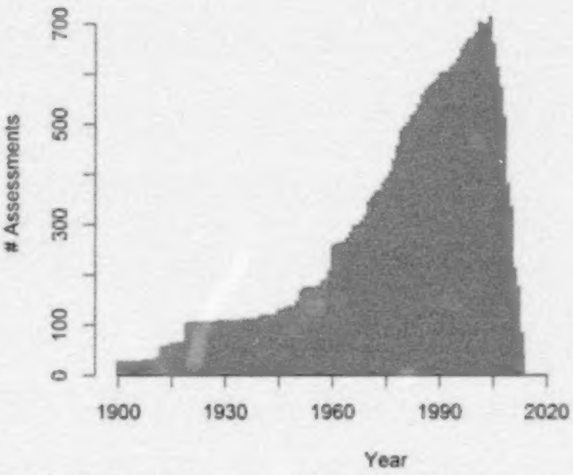

Figure 41-2. Temporal coverage of assessments included in metadata.

In addition to highlighting current trends and data gaps, the metadata repository can also be readily examined by local and regional experts to identify data that exist but have not yet been compiled or made more widely available. This is indeed one key benefit of archiving metadata in an integrated manner. Ideally, this then forms a living database where available information is used by researchers for interdisciplinary analyses, and new information is added as it becomes available.

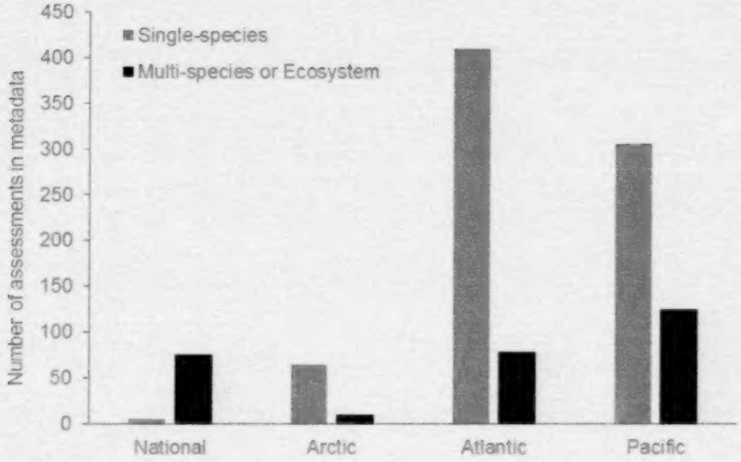

Figure 41-3. Spatial coverage of assessments included in metadata, by type (single-species, and multi-species or ecosystem-based).

The integrated database on Canadian ocean resources introduced here aims to contribute to the amount, quality and accessibility of data on a range of topics. This searchable—and freely-available—repository will contribute to creating a holistic understanding of ocean ecosystem and resource status and trends, and identifying emerging knowledge gaps. Ultimately, this will help academic and community researchers to access quantitative and qualitative data to help inform and support policy makers in efforts to improve and inform marine governance and future research. Other regions can use this effort as a template for improving integration of qualitative and quantitative data on marine resources, thus enhancing understandings of community, environment, and policy dynamics, and contributing to the sustainable use of those resources.

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Individual reports on conditions in freshwater

42. FRASER RIVER ENVIRONMENTAL CONDITIONS AND VARIATIONS IN SOCKEYE SALMON SURVIVAL

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42.1. Highlights

- In 2015, warm Pacific oceanic conditions and extreme weather patterns influenced seasonal patterns in Fraser River water temperature and discharge, including:
    - day of year record high discharge in February and March and low discharge in July for the Fraser River at Hope,
    - day of year record high water temperatures in May, June and July, and the largest daily mean deviation for the Fraser River at Hope, and
    - uncertain impact of early freshet and warmer temperatures on smolt outmigrants.
- High water temperatures were associated with widespread *en route* loss estimates for most Fraser sockeye stocks, but water conditions improved for spawning periods
- Our current research is focused on population level variability in abundance in response to dynamic freshwater environmental conditions; this includes evaluating nursery lake conditions, fry growth and survival, smolt and adult migrations, and carry over effects between freshwater and marine environments

42.2. Summary

The Fraser River basin has a complex and highly variable geography making local scale predictions of climate impacts on water conditions challenging. This large variability in geoclimatic conditions within the watershed can result in near normal air temperature and precipitation conditions in some areas and large anomalies in others, despite common large scale climate drivers. In 2015, the presence of a high water temperature anomaly, or "Blob", off the coast of B.C. and strong El Niño conditions were driving climate patterns throughout the province, and in turn affecting the freshwater discharge and temperature conditions.

- Winter snowpack was variable; Coastal B.C. was very low while the Central Interior was near normal.
- Spring precipitation was variable: South Coast and Southern Interior snowpacks were extremely low while Central and Northern Interior were near normal.
- Winter air temperatures were consistently above average, corresponding to over 40 days in February and March when Fraser River discharge at Hope exceeded previous daily records for a 103 year period.
- Water temperatures in the lower Fraser were consistently above average from January until May, with temperatures in May 1 to 3 °C above normal.

- Discharge levels were above average for April and May (Figure 42-1) and Fraser River peak freshet timing in 2015 was one week earlier than normal at Hope.
- Persistently warmer spring conditions resulted in extremely low June snowpack for the majority of the province, resulting in an early freshet and low summer discharge conditions in the Fraser River.
- Low early summer discharge combined with an extreme warm weather event in late June to early July to create record seasonal water temperatures for mid-July (Figure 42-2).
- Largest daily water temperature deviation from the mean (>5.0 °C) in more than 60 years occurred at this time (Figure 42-2).
- Discharge levels in the lower Fraser River were below average for the upstream migration of the majority of returning sockeye populations (Figure 42-1), and approached day of year record low discharge values (103 year record) from mid-July to early August; some smaller tributaries had more severe low discharge conditions.

42.2.1. Impact on Sockeye Salmon Migration Conditions

In contrast to adult Sockeye Salmon migrations, there is currently a lack scientific knowledge on the impact of unusual environmental conditions on the survival of out migrating smolts, making predictions of smolt survival from 2015 difficult. For example, higher discharge rates could increase smolt migration rates and water turbidity, both of which could reduce exposure to predators in freshwater (McCormick et al. 1998). Alternatively, changes in ocean entry timing associated warmer temperatures and higher flows could place juveniles in the marine environment when food sources are less abundant. The impacts of high temperature and low discharge conditions are well documented for Sockeye Salmon (Johnson et al. 2012). The persistence of temperatures of 18 °C or greater were sustained for the entire summer. Salmon migrating in temperatures above 18 °C show signs of decreased swimming performance (Eliason et al. 2011). Sustained temperatures above 20 °C can lead to increased mortality, disease, and legacy effects on egg quality (Burt et al. 2011). Fortunately, the low discharge conditions in early summer did not persist into peak spawning times, as low discharge on spawning grounds can affect spawning success (e.g. crowding due to less available spawning habitat) and egg survival (dewatering of redds). The adverse adult migration conditions in 2015 contributed to the high overall preliminary loss estimates for the major sockeye populations, ranging from 20 to 80% across stock groupings. Unlike *en route* loss, egg retention was not above average for most stocks, ranging from 1 to 50%. This improvement is consistent with the more benign environmental conditions for terminal areas as the summer progressed.

42.2.2. Variation in Fraser Sockeye Populations

Oceanic conditions and weather patterns influence freshwater environmental conditions, which in turn influence juvenile and adult survival of Fraser River Sockeye Salmon. Our group is interested in studying the mechanisms behind the large variation in survival among Fraser River Sockeye Salmon populations. More specifically, we are interested in the role of environmental conditions and trophic interactions within these systems and expected responses to future climate scenarios. Prior work has focused on the adult upstream migration with limited information on juvenile sockeye during freshwater life stages (Johnson et al. 2012). Therefore, the first step is to document the variation in the freshwater biological and physical environment for juvenile sockeye. For example, there is an 8-fold variation in primary productivity (mean photosynthetic rates) across Fraser sockeye nursery lakes. This translates to variation in prey species, competition for food with other species, and in abundance of predators. These dynamic lake environments affect the interannual variation in size, abundance and energy condition (percent lipid) of sockeye fry within and amongst populations. Understanding energy condition and minimum energy requirements of smolts leaving fresh water may allow for improvements in survival estimates and adult return forecasting. In addition, we are exploring carry over effects of changing phenology, energy, pathogens and abundance in freshwater on early marine survival. This speaks to the need to integrate research across disciplines to understand population dynamics in Fraser River Sockeye Salmon.

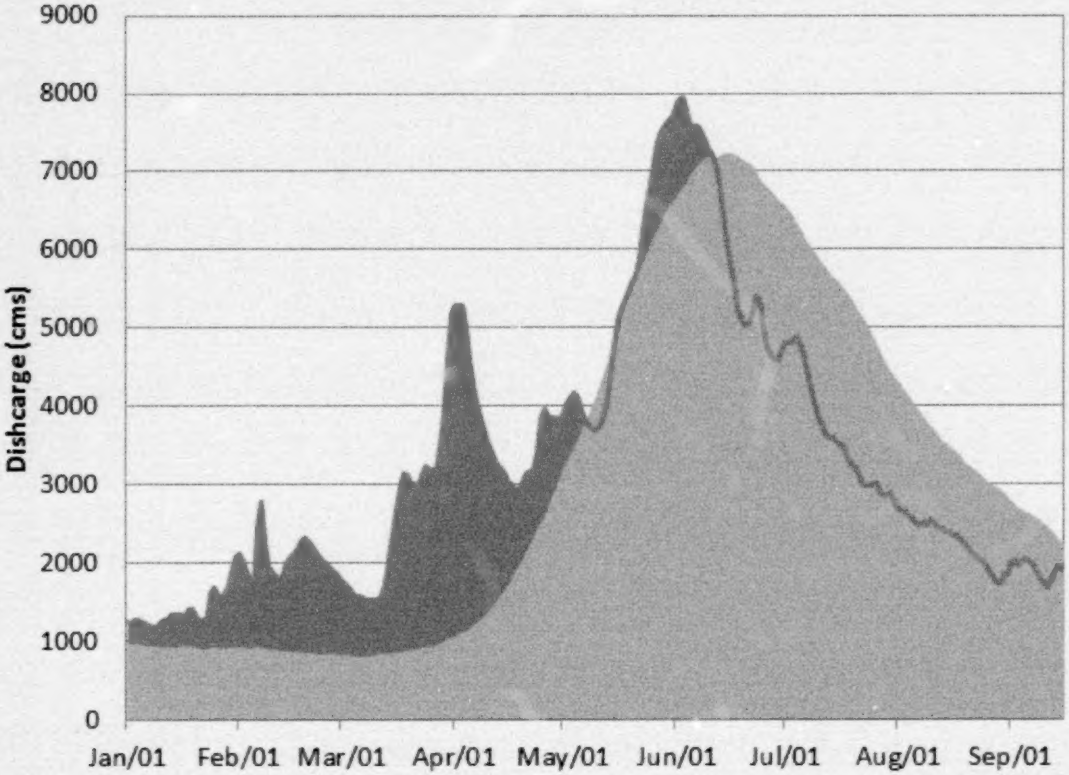

Figure 42-1. Fraser River discharge (cms – cubic meters per second) at Hope in 2015 (blue) and historic mean (green) of the 103 year period of record for this location. Data courtesy of Water Survey of Canada.

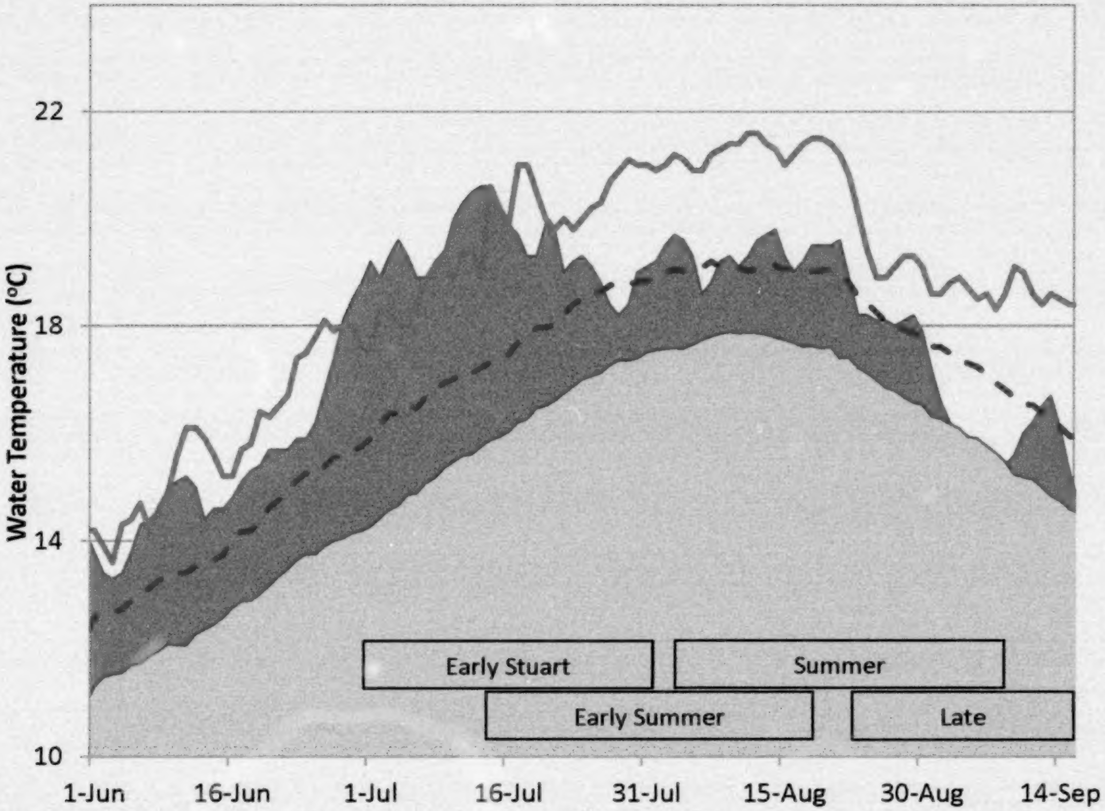

Figure 42-2. Fraser River water temperature at Hope in 2015 (red), in comparison to the previous 60 year mean (green), and 60 year maximum (blue). The dashed line is 1 standard deviation from the mean. The migration timing of each of the four major Sockeye Salmon run timing groups (through the lower Fraser River at Mission) is represented by labelled rectangles. Data collected by Water Survey of Canada and DFO Environmental Watch Program.

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43. A SATELLITE-BASED STUDY OF CHLOROPHYLL IN CHILKO LAKE AND APPLICATION TO SOCKEYE SALMON

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[4]University of Victoria, Victoria, B.C.

43.1. Highlights

- A chlorophyll time series (2002-2012) has been validated for Chilko Lake based on the European MERIS sensor aboard the ENVISAT satellite.
- Secondary metrics including the yearly timing of bloom initiation and bloom peak have been calculated for five lake subareas. Bloom initiation and peak are usually earliest in Franklyn Arm and the south end of the lake, with initiation occurring in central and northern regions up to 50 days later. The bloom peak was late in 2008 and early in 2009.
- Correlational studies with sockeye data suggest that early blooms are associated with larger smolts, and strong summer primary production is associated with better growth, freshwater survival, and smolt survival.

43.2. Summary

Satellite-based estimates of phytoplankton chlorophyll are commonly used for coastal and offshore studies (e.g. Carswell et al. 2016; Gower and King 2016,), and standard image products are routinely distributed by NASA for a number of ocean colour sensors including MODIS, SeaWiFS, MERIS, and most recently, VIIRS. However, the algorithms applied in marine systems are not necessarily suitable for freshwater systems. In particular, they cannot be applied in a system such as Chilko Lake, which is ultra-oligotrophic and seasonally subject to extreme levels of glacial turbidity. The other challenge to using satellite products for lakes is their low spatial resolution. MODIS, SeaWiFS, and VIIRS all have 1-km pixels, whereas MERIS with 300-m pixels is more suitable for a waterbody such as Chilko Lake, which is 5 km wide at its widest point.

Using field measurements made by DFO in 2009-2011, we validated a selection of published chlorophyll algorithms applied to MERIS imagery. Of four algorithms tested, the most accurate retrievals were obtained using the Case 2 Regional Processor (C2R; Doerffer and Schiller 2007). The FUB/WeW Processor (Schroeder et al. 2007) consistently underestimated chlorophyll, and the boreal lakes variant of C2R (Koponen et al. 2008) and Fluorescence Line Height (FLH; Gower et al. 1999; Gower and King 2007) were both affected by turbidity (Figure 43-1).

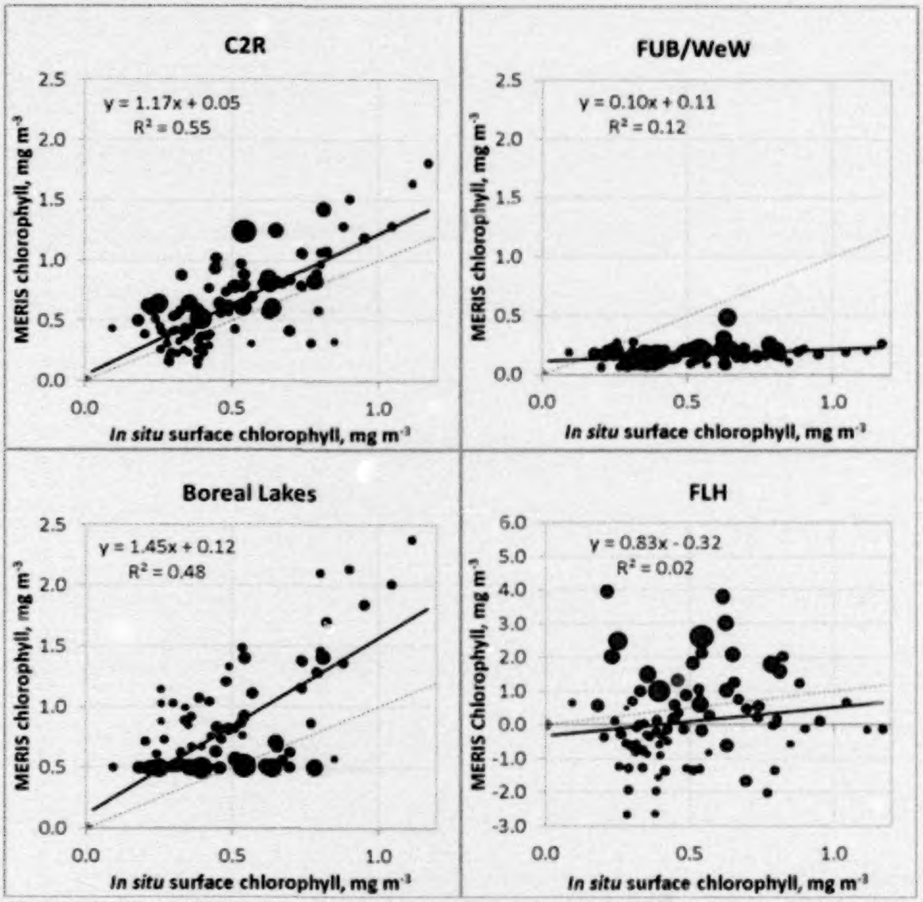

Figure 43-1. Validation of four chlorophyll algorithms applied to MERIS images of Chilko Lake. Symbol size is proportional to water turbidity. Dashed lines indicate 1:1 relationship.

A 2002-2012 time series was constructed of the C2R product and used to characterize the seasonal cycle of chlorophyll in five subregions of Chilko Lake, as well as its year-to-year variability. A sample time series is shown in Figure 43-2. Secondary metrics were computed from the time series, including:

- 8-day, monthly, and annual chlorophyll averages
- timing of bloom initiation
- timing of the chlorophyll peak
- cumulative chlorophyll.

Although there was within-lake variability, the annual cycle illustrated in Figure 43-2 and Figure 43-3 shows a fall peak with a maximum in October and a minimum in April. Over the ten-year time series, peak chlorophyll seldom rose above 1.2 mg m^{-3}, although there were occasional high chlorophyll events. Bloom initiation (defined as the year-day when chlorophyll levels first rise a small threshold above the annual median; Siegel et al. 2002) varied between late May in the south end of the lake and as late as early July in the central and northern regions. 2009 was a notably early year (Figure 43-4). The bloom peak was also later in the northern part of the lake than the southern part, and was notably late in most subregions in 2008.

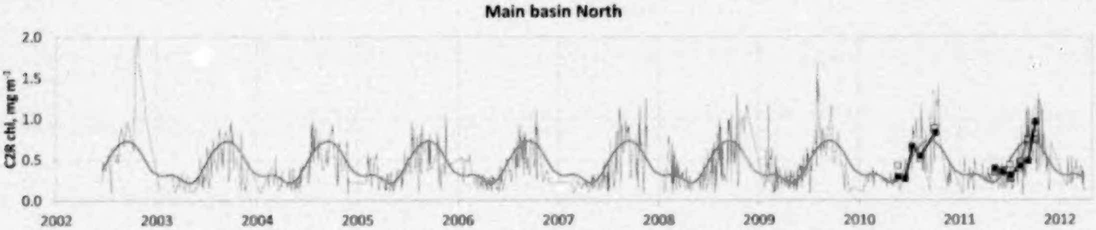

Figure 43-2. Chlorophyll time series for the northern basin of Chilko Lake based on the C2R algorithm. The red line shows an annual canonical cycle and the black, green and blue symbols denote DFO field observations made in 2010 and 2011.

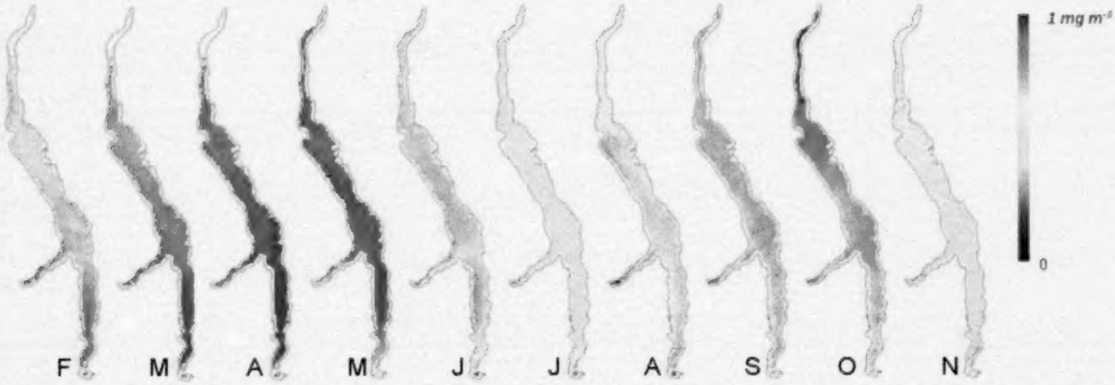

Figure 43-3. Average monthly chlorophyll (2002-2012) in Chilko Lake. January and December images are not shown due to limited winter satellite coverage.

Chlorophyll metrics were used in a correlational study that compared lake primary production with sockeye freshwater and marine survival and smolt size. Preliminary results suggested that for the freshwater year (i+1) of the life cycle of Sockeye Salmon:

- Early blooms produce larger smolts.
- There is better freshwater survival with early blooms in the north end of the lake.
- Strong summer primary production improves growth, freshwater survival, and smolt survival.

In addition to these results it was found that strong early spring primary production in the smolt year (i+2) before the fish leave the lake was associated with better smolt survival.

Because MERIS failed in 2012, the chlorophyll time series could not be extended beyond 2012; however a continuation mission, Sentinel-3A, was launched in February 2016, which should enable a resumption of the time series once that mission becomes operational in the fall 2016.

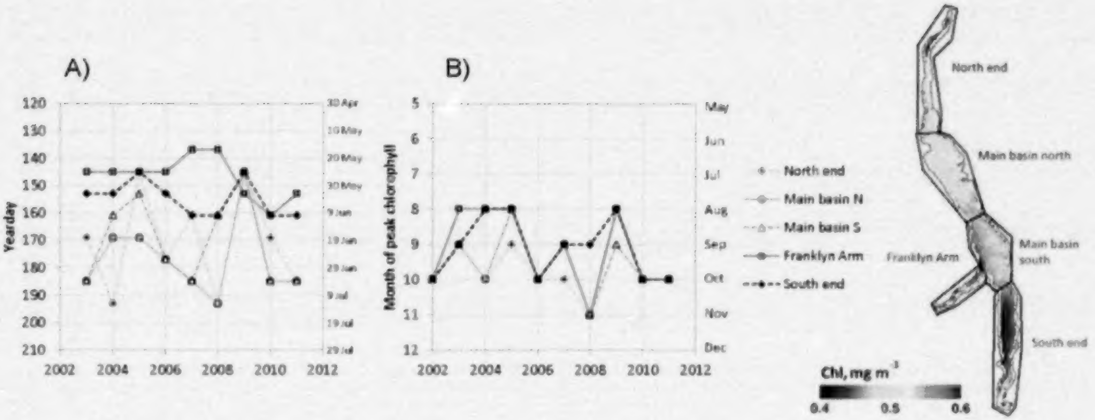

Figure 43-4. A) Timing of bloom initiation, and B) timing of peak chlorophyll, for the five Chilko Lake subregions. The image at right shows the 2002-2012 overall mean chlorophyll concentration.

43.3. References

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44. SALMON RESPONSES TO HYDROCLIMATOLOGICAL CONDITIONS IN BRITISH COLUMBIA IN 2015

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44.1. Highlights

- Multiple years (2014, 2015) of warm ocean conditions have had a pervasive influence on terrestrial and freshwater ecosystems in B.C.
- Anomalously high winter flows and/or temperatures in freshwater systems in 2014/15 were associated with major production anomalies for some salmon populations (anomalously low fall-to-spring fry survival of <25% for sockeye in Barkley Sound nursery lakes; anomalously high egg-to-fry survival of >8% for Okanagan sockeye in winter 2014/15).
- Anomalously high winter runoff and subsequent hydrological drought in summer-fall combined with record breaking summer temperatures induced widespread losses of summer migrating salmon adults and rearing juveniles for many species populations in river and stream networks throughout southern B.C. and the Pacific Northwest.
- Hydrological drought, sub-average discharge and extreme river temperatures produced anomalously high, *en route*, mortalities for "summer-run", adult sockeye returning to spawning grounds in: the Okanagan River (>90% *en route* mortality), Vancouver Island's Sproat River (hundreds of pre-spawn losses) and the Fraser River (various populations exhibiting 20-50% pre-spawn losses).
- The B.C. Environment Minister suspended an unprecedented number of water licenses (50) normally permitting irrigation withdrawals from the Nicola River system in the southern B.C. interior to maintain flows for fish in summer 2015.
- Sport fisheries were closed for the majority of rivers throughout Vancouver Island plus hundreds of freshwater sites throughout Washington State in 2015 given concerns for temperature-discharge impacts on resident fish survival.
- Largely negative impacts of freshwater conditions in 2015 on multiple species, populations and life history stages of salmon throughout southern B.C. and the Pacific Northwest are likely to contribute to an anticipated pattern of sub-average productivity and/or returns for the next few years in this geographic area.

44.2. Summary

Outcomes of many life history events and processes of Pacific Salmon are profoundly influenced by annual to decadal-scale variations in freshwater discharge and thermal regimes. Freshwater regimes are controlled by complex atmospheric, ocean climate and hydrological linkages which have been the focus of renewed research interest given the potential threats posed by climate change to all forms of water use as well as to the sustainable management of salmon involving long-term investments in controlled exploitation, conservation, hatchery production, stock and habitat restoration activities (Shanley et al. 2015).

Recent research by some authors (Black et al. 2014, Coulthard and Smith 2015) has provided compelling evidence that large-scale atmospheric drivers (e.g. the North Pacific High) may

induce simultaneous, annual to decadal-scale changes in marine ecosystems (e.g. intensity of upwelling and associated production variations in the California Current System), terrestrial ecosystems (e.g. coastal zone precipitation and tree growth patterns from northern Baja to Vancouver Island) and associated freshwater ecosystems (e.g. discharge and seasonal thermal regimes). The strength and direction of associations among major atmosphere, earth and freshwater process drivers exhibits considerable statistical complexity when considered over even the limited geographic extent of British Columbia and the Yukon (Fleming and Whitfield 2010, O'Neel et al. 2015, Fleming et al. 2016). Consequently, the emergence of regionally coherent response patterns by Pacific Salmon to changes in freshwater regimes induced by climate variation and change effects appears to be less frequent or predictable than regime changes in marine ecosystems (e.g. Hyatt et al. in this and previous state of the ocean reports). That said, the consecutive occurrence of anomalously warm water in the North Pacific in 2014-2015 and of a major El Niño in 2015-2016 has been associated with a geographically expansive "footprint" of disrupted life history events for salmon driven by associated anomalous discharge and thermal conditions in stream and river networks throughout the Pacific Northwest and southern British Columbia.

Elsewhere in this report, Anslow et al. 2016 have provided detailed documentation of hydroloclimatological conditions prevailing in 2015 across British Columbia in association with anomalously warm waters of the northeastern Pacific Ocean in 2014-2015. In particular, winter through spring air temperatures set a record high in the southwestern 2/3's of the province such that snow accumulation was below normal in the southeast and extremely low in all southwest B.C. catchments. Further, positive stream flow anomalies were above the 90th percentile for hydrometric stations throughout much of B.C. during spring 2015 and approaching record dry conditions for July-Sept (see Figure 5-5 of Anslow et al. 2016). Estimates of net weekly inflows from the aggregate of variably sized tributary streams to Okanagan Lake (Figure 44-1) and the much larger Columbia River (Figure 44-2) reveal the shifting continuum from near record high to near record low seasonal discharge patterns that were apparent in major river systems (e.g. the Fraser, North Thompson, Cowichan, Somass) as well as their minor tributaries throughout southern B.C. and the Pacific Northwest.

Record high seasonal temperatures accompanied the summer-fall interval of low discharge in the same river networks (Figure 44-3) and together with anomalous flow conditions strongly influenced life history events for fish populations throughout large expanses of B.C., Washington State, Idaho and Oregon in summer 2015.

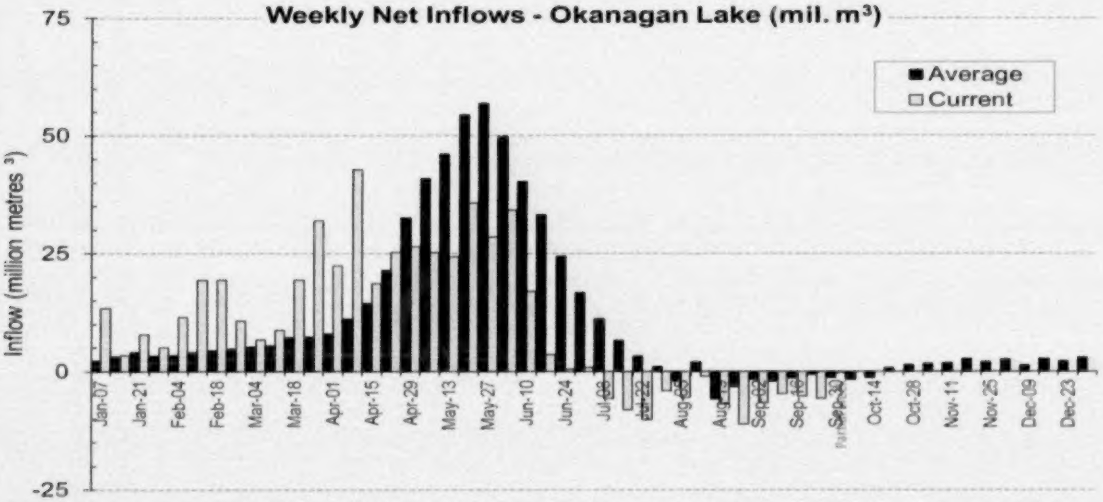


Figure 44-1. Current year (i.e. 2014-15) seasonal, net-inflows from tributary streams to Okanagan Lake. Winter inflows in 2015 were exceptionally high with an early freshet that was common to south interior basins that normally experience winter "drought" and late spring freshets e.g. Okanagan February flows were four times normal; freshets occurred in February to early April versus a May to June norm (Data sources as per Hyatt et al. 2015).

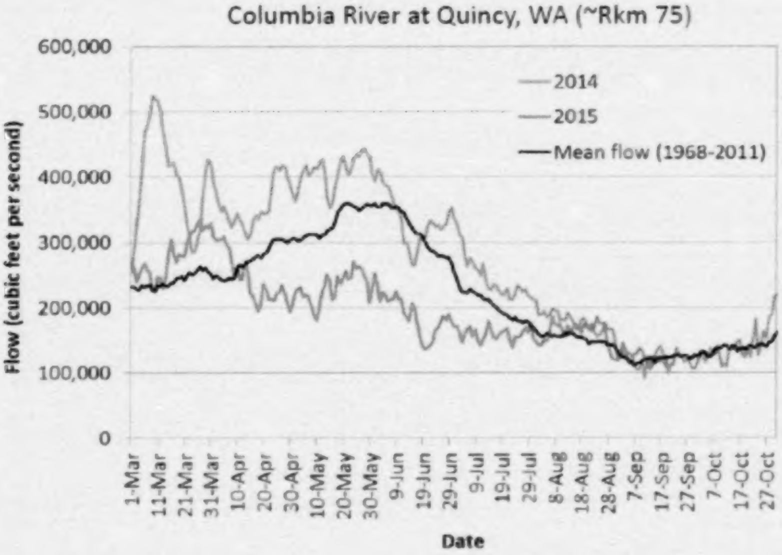


Figure 44-2. Timing and magnitude of spring-summer flows in the Columbia River exhibiting anomalous winter increases, summer reductions in 2015 relative to the 1968-2011 all-year average. Similar seasonal patterns were apparent in major river systems (e.g. the Fraser, North Thompson, Cowichan, Somass) as well as their minor tributaries throughout southern B.C. and the Pacific northwest.

Low river flow+
hot spring
= high river
temperatures &
fish kills

Sockeye salmon

White sturgeon

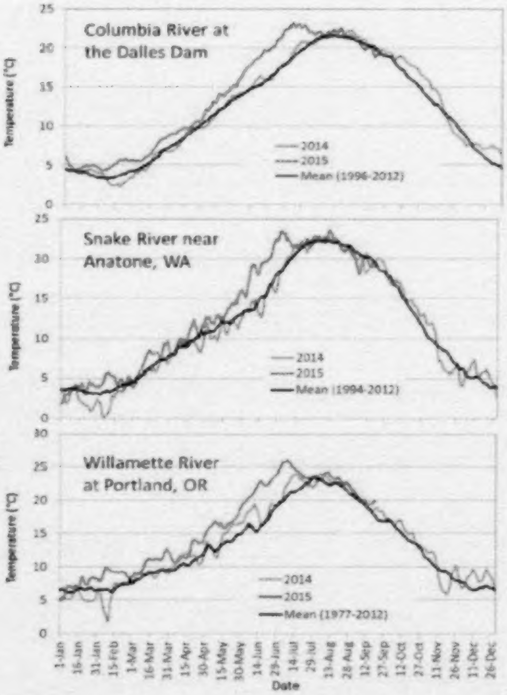
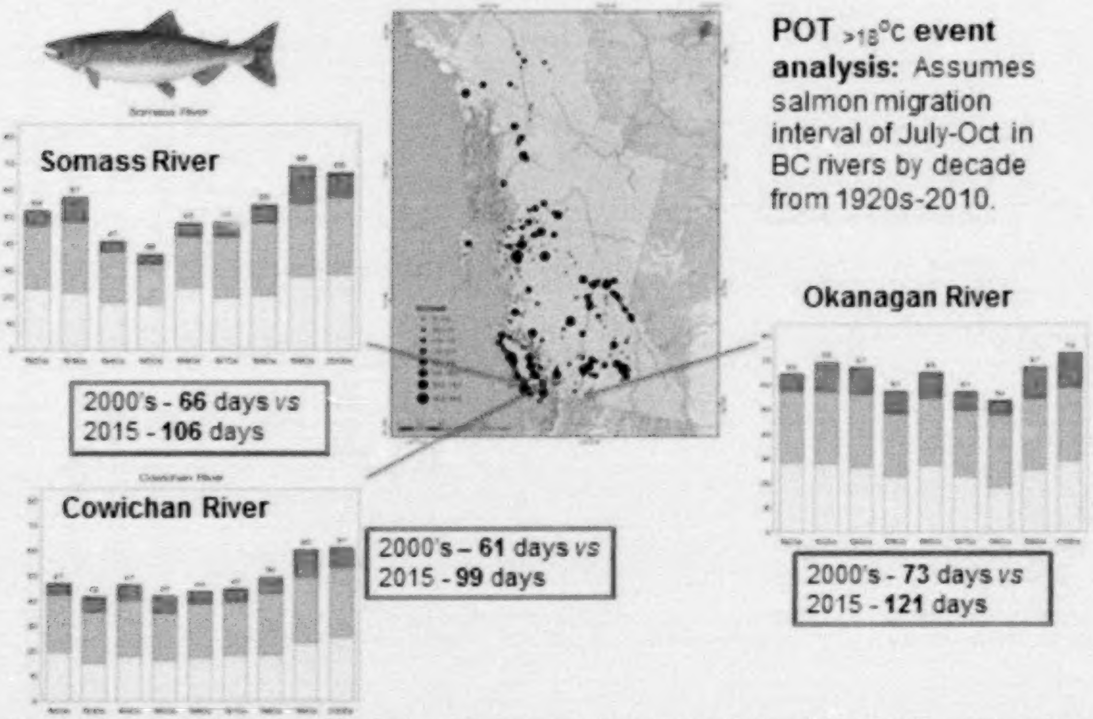


Figure 44-3. Timing and magnitude of seasonal temperatures in the Columbia, Snake and Willamette rivers exhibiting above average values through the late winter of 2014/15 followed by record breaking highs in summer 2015 relative to the 1994-2012 all-year average. Similar, seasonally anomalous temperatures observed in these Pacific Northwest rivers were apparent in major river systems (e.g. the Fraser, North Thompson, Cowichan, Somass) as well as their minor tributaries throughout southern B.C. Numerous reports of mortality events for salmon and other fish species were also reported to the authors for these same locations (Figure complements of Laurie Weitkamp, NOAA Fisheries).

Prolonged exposure to temperatures that exceed 18 °C has been repeatedly identified as stressful and associated with elevated incidence of disease outbreaks, slowed progress and elevated mortality for adult salmon migrating to their systems of origin to spawn (McCullough et al. 2001, Hyatt et al. 2015). Retrospective analysis of the frequency of occurrence of mean daily water temperatures that peak-over-threshold 18 °C ($POT_{>18^{\circ}C}$) in a sample of southern B.C. rivers (Somass, Cowichan, Okanagan rivers) provides a means of assessing the potential significance of stressful conditions for salmon migration during summer 2015 relative to decadal-scale averages (Hyatt and Stiff, unpublished results). Results from this analysis (Figure 44-4) indicate the frequency of stressful temperatures during the main summer-fall migration interval for species such as Chinook and Sockeye Salmon was elevated by between 37-48 days (i.e. a 54 to 66% increase) relative to the highest mean value of the index for any decade between the 1920s and 2000's.



POT $_{>18°C}$ event analysis: Assumes salmon migration interval of July-Oct in BC rivers by decade from 1920s-2010.

Somass River

2000's - **66** days *vs*
2015 - **106** days

Cowichan River

2000's – **61** days *vs*
2015 - **99** days

Okanagan River

2000's - **73** days *vs*
2015 - **121** days

Figure 44-4. Decadal means of an index of the average frequency of stressful thermal conditions (mean daily $POT_{>18°C}$) likely to be encountered by adult salmon migrating towards spawning grounds in three southern B.C. rivers. Separate colours in histogram bars signify values separated roughly by terciles of the migration interval. Boxed values indicate the cumulative number of $POT_{>18°C}$ index observations in 2015 relative to the average for the most recent decade of the 2000s (Hyatt and Stiff, unpublished results).

The annual migration success of thousands of salmon populations returning to B.C. river and stream networks is only rarely quantified. However, quantitative and qualitative observations of elevated *en route* mortalities observed for adult salmon returning to the Somass (above average pre-spawn losses), Cowichan (above average pre-spawn losses) , Okanagan (>90% *en route* losses) and Fraser systems (20-50% losses for some summer run populations; Dave Patterson, DFO, personal communication) in 2015 suggests the widespread occurrence of such events. The potential extent of elevated losses of salmon is likely to coincide with drought levels mapped by the B.C. River Forecast Centre (Figure 44-5) which provides a clear indication of the geographic boundaries for the extremely hot and dry conditions that prevailed within southern B.C. during summer-fall 2015.

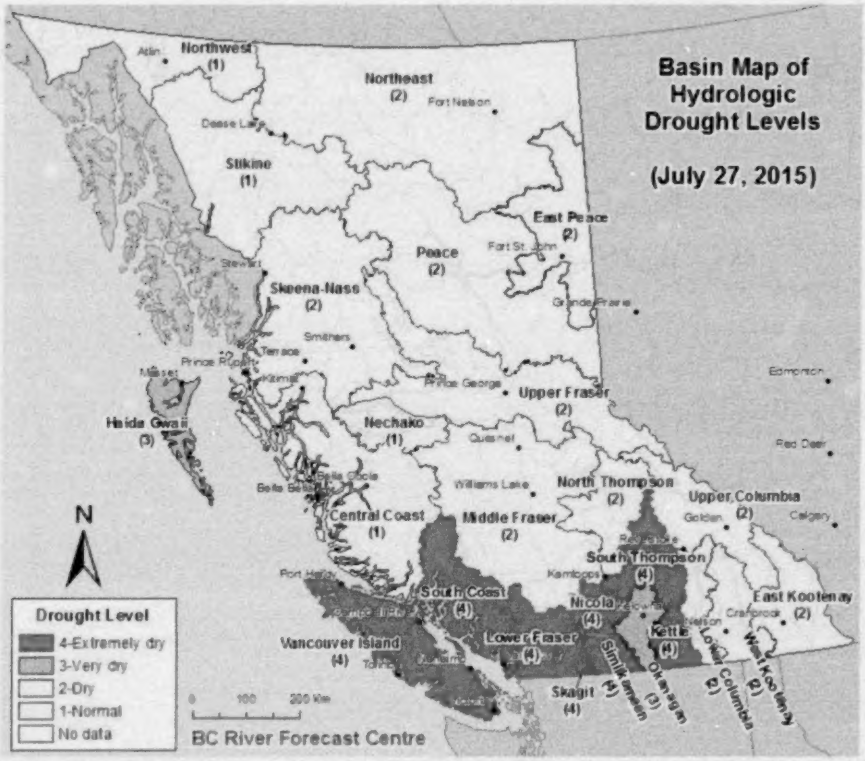

Basin Map of Hydrologic Drought Levels
(July 27, 2015)
Northwest (1)
Northeast (2)
Stikine (1)
East Peace (2)
Peace (2)
Skeena-Nass (2)
Upper Fraser (2)
Haida Gwaii (3)
Nechako (1)
North Thompson (2)
Upper Columbia (2)
Central Coast (1)
Middle Fraser (2)
South Thompson (4)
South Coast (4)
Nicola (4)
East Kootenay (2)
Vancouver Island (4)
Lower Fraser (4)
Kettle (4)
Similkameen (4)
Okanagan (3)
Lower Columbia (2)
West Kootenay (2)
Skagit (4)
Atlin
Fort Nelson
Dease Lake
Fort St. John
Stewart
Grande Prairie
Smithers
Terrace
Prince Rupert
Masset
Kitimat
Prince George
Edmonton
Quesnel
Red Deer
Bella Coola
Bella Bella
Williams Lake
Golden
Calgary
Revelstoke
Kamloops
Port Hardy
Kelowna
Nelson
Cranbrook
Tofino
N
Drought Level
4-Extremely dry
3-Very dry
2-Dry
1-Normal
No data
0 100 200 Km
BC River Forecast Centre

Figure 44-5. B.C. River Forecast Centre map of the geographic extent of severe hydrologic drought (stage 3 and 4) levels existing throughout British Columbia during the mid-summer-fall interval (July-Sept).

Quantitative assessments of annual performance levels for freshwater life history stages of salmon, other than migrating and/or spawning adults, (e.g. incubation, summer rearing, overwintering, juvenile migration) are too sparse to provide much more than anecdotal observations of regionally representative responses to annual hydrological system variations. However, an abundance of such observations received by the authors through the summer and fall of 2015 suggest that multiple life-stages of salmon likely experienced significant departures from average performance in systems throughout southern B.C. where it appears there were: (1) catastrophic losses of overwintering sockeye fry (50-90%) in Barkley Sound nursery lakes that experienced temperature elevations of 1.5-2.5 degrees through the winter of 2014-2015, (2) record breaking fry recruitment of wild sockeye to Osoyoos Lake in spring 2016 suggesting benefits of above average discharge in the Okanagan River to egg/alevin incubation success in winter 2014-2015, (3) poor quality eggs from Okanagan adult sockeye screened in fall of 2016 for hatchery propagation and (4) delays, habitat displacement and losses of several species of juvenile and adult salmonids (Chinook, Coho, Steelhead etc…) in the Cowichan River during the late summer-fall drought of 2015 (Craig Wightman, B.C. Conservation Foundation, pes. comm.).

Finally, advisory responses of field biologists, fisheries and water managers reflected the severity of freshwater conditions in summer 2015 which prompted: (1) suspension of 50 water licenses, normally permitting irrigation withdrawals from the Nicola River, by the B.C. Environment Minister (Glen Davidson, B.C. Forest, Lands and Natural Resource Operations, personal communication), (2) recreational fisheries closures for the majority of Vancouver Island rivers plus hundreds of sites in Washington State given anomalous discharge, temperature and fish performance concerns.

In summary, anomalous atmospheric and freshwater conditions from the late summer of 2014 through the fall and winter of 2015-2016 appear to have induced multiple responses by several species and life stages of Pacific Salmon throughout southern B.C., Washington and Oregon in 2015. Much, although not all, of the evidence suggests that responses were survival-unfavourable such that future production of many salmon populations in this geographic area may be expected to decline for a few years in the absence of compensatory responses at other life stages in marine environments. Observations throughout this year's state of the ocean report do not support the hypothesis for the occurrence of strong compensatory responses in marine ecosystems in 2015 and the occurrence of a powerful El Niño event in the winter through summer of 2015-2016 offers little assurance that effects to increase salmon productivity are likely to occur in the immediate future (see Hyatt et al. 2016).

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45. APPLYING FRESHWATER METADATA IN STOCK-RECRUIT MODELS FOR CHILKO LAKE SOCKEYE SALMON

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45.1. Highlights

- Efforts to increase the production of Chilko Sockeye included (*a*) fertilizing the lake, (*b*) opening a spawning channel, (*c*) increasing escapement, (*d*) a decrease in post-smolt survival (marine survival) and (*e*) decreasing fishing mortality (in order to affect *c* despite *d*).
- The spawning channel cut egg-to-smolt survival in half. Changes in freshwater habitats are just as important as changes in marine habitats.
- The effect of fertilizer (1988, 1990-1993) on survival is not clear, and complicated by problems with data for the 1989 brood year that would have been affect by 1990 fertilizer: no smolts estimate and an 8 SD outlier for total survival.
- Egg-to-smolt survival increased 300% when the channel closed, compared to when it was open. Increased primary production in Chilko Lake (73% in 20 years) may explain increased egg-to-smolt survival. Thus natural fertilization (source not known) may have done what artificial fertilization intended.
- When factors derived from historical metadata were included in stock-recruit analyses, that provided value by (a) reducing the total variance to be explained before considering the effect of stock density, and (b) reducing the effect of apparently imprecise estimates.
- For this, and presumably other stock-recruit datasets, we need to find, mobilize, and apply more factors from the historical metadata to "clean" the stock-recruit data, including factors for the relative precision of observations.

45.2. Summary

Efforts to increase the production of Sockeye Salmon (*Oncorhynchus nerka;* Walbaum 1792) from Chilko Lake (Fraser River watershed) included simultaneously fertilizing the lake (1988, 1990–1993) and operating a spawning channel (1988–2004). To improve our understanding of mechanisms underlying variability in survival time series and to investigate the effects of these enhancement projects, we analyzed data for spawners, smolts, and returns along with metadata for these salmon and their watershed.

Beverton and Holt (1957) models fitted to three life-history intervals (Figure 45-1) showed higher productivity and capacity before and after the period of spawning channel operation (1988-2004). The deleterious effect of the channel is thought to be high mortality for newly-emerged salmon fry that swim upstream in the shallow edges of the Chilko River to enter Chilko Lake,

with many fry (a) swept back downstream by the outflow from the spawning channel, and/or (b) trapped in the spawning channel and killed by birds (Timber Whitehouse and Keri Benner, DFO, Kamloops, personal communication).

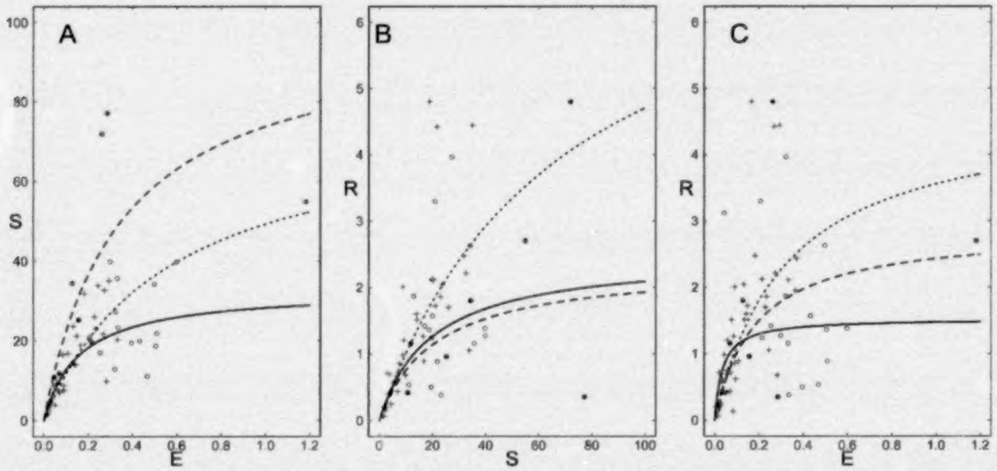

Figure 45-1. Beverton and Holt models fitted to Chilko Lake Sockeye Salmon. A) smolts ×10^{-6} from effective female spawners ×10^{-6}; B) adult returns ×10^{-6} (before fishing) from smolts; and C. returns from effective female spawners. Points as "+" and the dotted line are data from before the spawning channel, affecting broods1949–2007; "o" and solid line is during the spawning channel, broods 2008–2003; and "" and dashed line is after the spawning channel, broods 2008–2010.*

Analyses of other possible confounding effects included an examination of fecundity and primary productivity trends. Fecundity does not explain the decrease in apparent eggs-to-smolt survival when the channel was open, but we noted a long-term decrease in fecundity-at-length (corrected to a standard length by annual regressions) for Chilko Sockeye (Figure 45-2).

Despite not being able to demonstrate that fertilizing Chilko Lake produced a useful increase in effective female spawners (EFS)-to-smolt survival, we note that a large increase (300%) in EFS-to-smolt survival after the channel was closed compared to when it was open. This appears to be the result of a 73% increase in the primary productivity of Chilko Lake in the last 20 years (Table 45-1). Trends in fecundity and lake productivity show that the "natural sockeye ecosystem" varies in important ways at decadal scales.

Table 45-1. Primary production estimates for Chilko Lake, showing that productivity has increased 73% in about 20 years and that productivity is presently greater than in years when the lake was fertilized. Note there is a 13 year gap in this time series (Unpublished data, Dan Selbie, DFO).

Years	**Primary Production May to October (mg C m^{-2} day^{-1})**
1985–1995 Not Fertilized	73 (n = 4, SD = 114)
1985–1995 Fertilized	93 (n = 5, SD = 27)
2009–2014 Not Fertilized	126 (n = 5, SD = 11)

We also applied metadata thought to represent the relative precision of returns estimates, a "variance factor" (Zuur et al. 2009, Gelman et al. 2013 §7.2) based on the proportion of the Chilko Lake Conservation Unit (CU) spawners in the mixture of co-migrating CUs Fraser River Sockeye (percent of run). Including this effect resulted in further uncertainty about the effect of lake fertilization because the returns for brood 2009 are the smallest recorded proportion of run (about 3.4% but that in itself is imprecise). The total survival (returns from EFS) for brood year 1989, thought to be affected by fertilizer added in 1990 (although smolts from 1991 were not counted), was eight standard deviations above the mean survival (calculated without 1989). That leaves four cases, one of which (brood 1987) was a partial application of fertilizer, and two of which (broods 1990 and 1991) experienced poor smolt survival (probably marine survival).

In similar retrospective analyses, researchers should recognize the potential utility of quality indicators for freshwater habitat and pay more attention to the assembly and analysis of appropriate metadata.

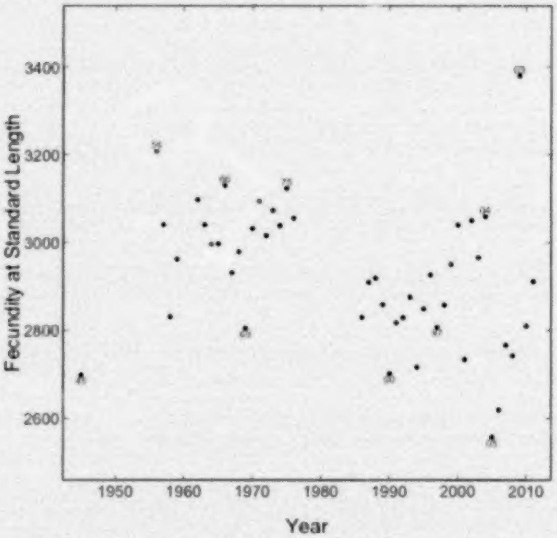

Figure 45-2. Fecundity for Chilko Sockeye, at a standard reference length (53.45 cm, the mean) has declined by about 17% from the 1950s to the 2010s. Females of age 1.2 and age 1.3 were pooled for this plot. Sample sizes are typically 50 fish except for the extremes: 2005 (n = 5) and 2009 (n = 4).

45.3. References

Akenhead, S.A., Irvine, J.R., Hyatt, K.D., Johnson, S.C., Grant, S.C.H., and Michielsens, C.G.J. 2016. Confounded Effects on Salmon Recruitment from a Spawning Channel and Lake Fertilization at Chilko Lake, British Columbia. Nor. Pac. Anad. Fish Comm. Bull. (submitted July 2015).

Beverton, R.H., and S.J. Holt. 1957. On the dynamics of exploited fish populations. Chapman and Hall, New York. 533p.

Gelman, A., Carlin, J.B., Stern, H.S., Dunson, D.B., Vehtari, A., and Rubin, D.B. 2013. Bayesian Data Analysis. Third Edition, Chapman and Hall, New York.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A, and G.M. Smith. 2009. Mixed Effect Models and Extensions in Ecology with R. Springer, New York.

46. SALISH SEA COHO SALMON DECLINES – IS THE PROBLEM IN THE OCEAN OR FRESH WATER?

James R. Irvine[1], Mara Zimmerman[2], Joe Anderson[2], Correigh Greene[3], and Marc Trudel[1]

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[3]National Oceanic and Atmospheric Administration, National Marine Fisheries Service,
Northwest Fisheries Science Center, Fish Ecology Division, Seattle, Washington, USA
Correigh.Greene@noaa.gov

46.1. Highlights

- Salish Sea Coho Salmon populations show consistent declines in smolt (marine) survival over time with no real breakpoints.
- Control (reference) coho populations outside Salish Sea do not have declining smolt survivals.
- Salish Sea Coho Salmon freshwater (pre-smolt) survivals have been highly variable but do not show evidence of declines over time.
- We conclude that factors operating in marine waters within rather than outside the Salish Sea or in freshwater appear to be responsible for declining returns of Coho Salmon to the Salish Sea.

46.2. Summary

Many populations of Coho (*Oncorhynchus kisutch*), Chinook (*O. tshawytscha*), and Steelhead (*O. mykiss*) Salmon returning to streams draining into the Salish Sea have experienced significant declines in recent decades. The Salish Sea Marine Survival Program was established to try to understand reasons for these declines (http://marinesurvivalproject.com/the-project/why/).

This program is based on the assumption that factors operating in the marine waters of the Salish Sea are responsible for declining numbers of adult salmon returning to freshwater. However, it is also possible that conditions outside the Salish Sea might be responsible for declines; these conditions could occur in marine waters outside the Salish Sea, or in freshwater. This research examines data for Coho Salmon to try to understand the relative importance of these different sources of mortality.

In their examination of smolt (i.e. predominantly marine) survival patterns of wild and hatchery Coho Salmon, Zimmerman et al. (2015) documented consistent declines in smolt survival over time with no real breakpoints for Salish Sea coho populations. In contrast, Coho Salmon populations outside the Salish Sea did not demonstrate decreasing smolt survivals (Figure 46-1). This suggests that the problem for Coho Salmon does not occur in the open ocean beyond the Salish Sea. However, it is still possible that declining survivals within fresh water might play a role in reduced returns.

To evaluate the role that freshwater conditions might have in declining returns of Salish Sea Coho Salmon, estimates of freshwater survival were assembled for several wild populations.

Coho returning to Black Creek on the east coast of Vancouver Island have the longest and most reliable time series for a Canadian population. At Black Creek, freshwater productivity (smolts/spawner) estimates were highly variable over the time series while smolt survivals decreased (Figure 46-2). Other populations within the Salish Sea had similar patterns, suggesting that conditions in fresh water were not responsible for declining returns.

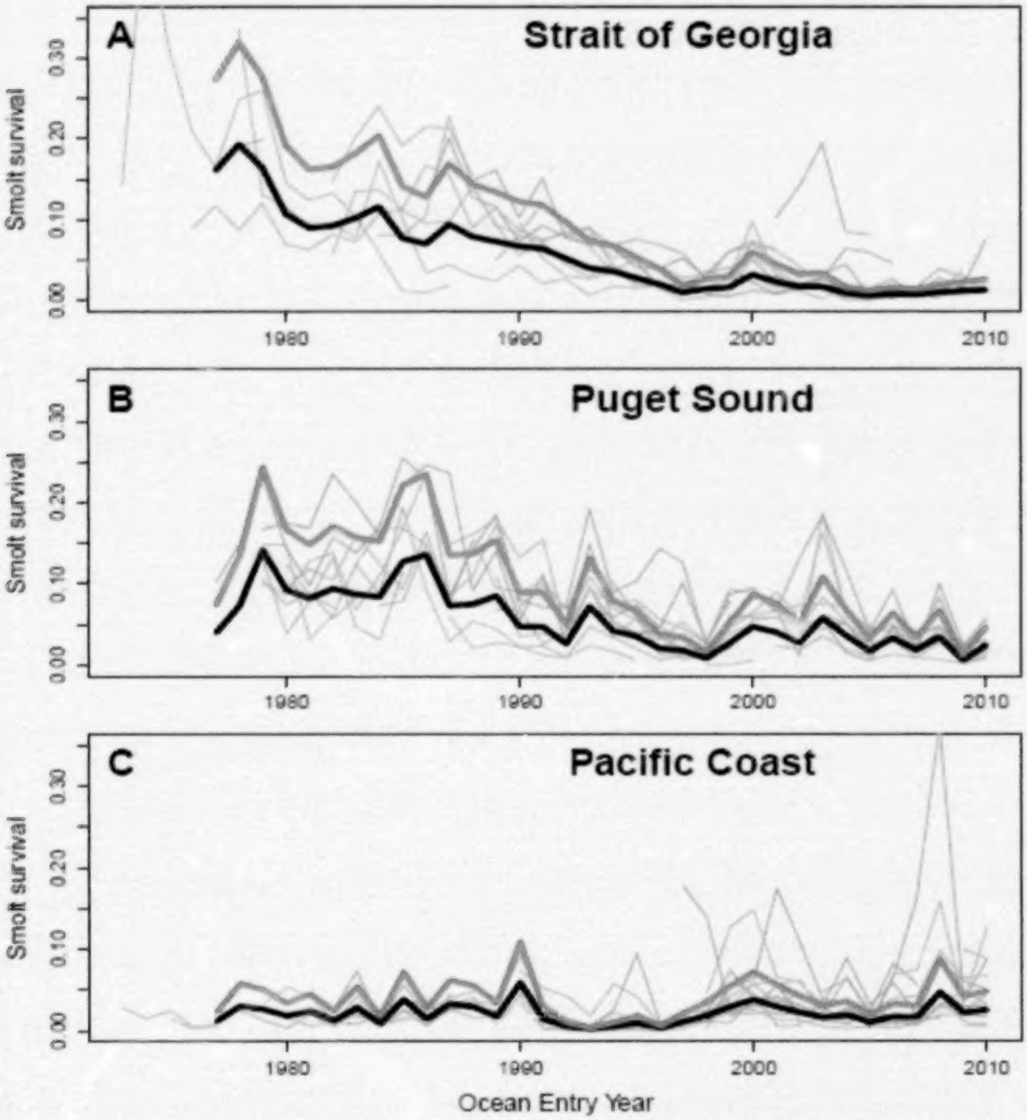

Figure 46-1. Wild (blue) and hatchery (black) Coho Salmon smolt survivals for populations in the Strait of Georgia, Puget Sound and outer Pacific Coast (i.e. controls) (from Zimmerman et al. 2015).

In conclusion, decreasing smolt survivals are chiefly responsible for declining returns of Coho Salmon to Salish Sea streams. Factors operating within rather than outside the Salish Sea appear to be responsible for these declines. Hugely variable freshwater survivals affect adult returns but there is little evidence that they are the major reason for declining Coho Salmon returns to the Salish Sea.

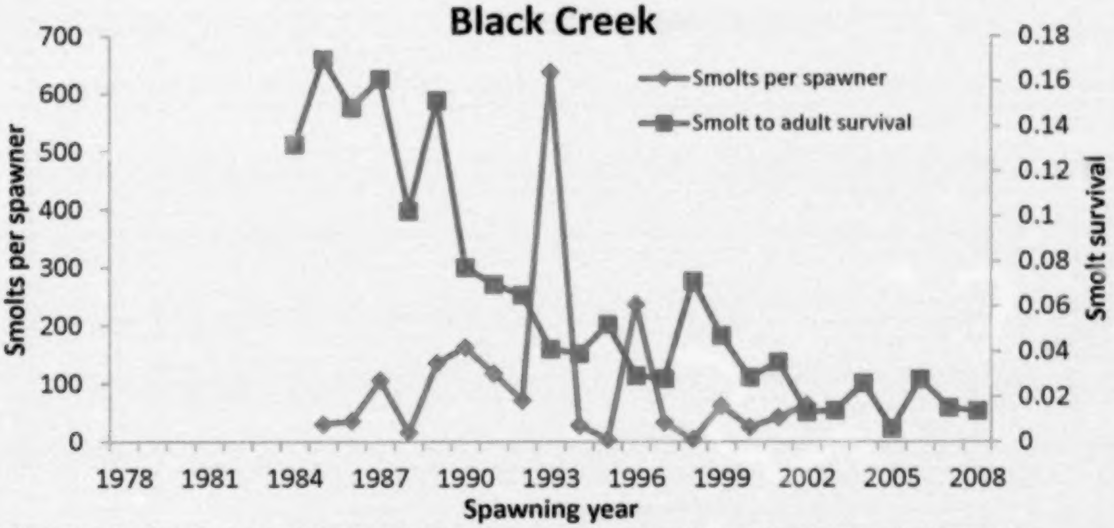

Figure 46-2. Trends in Coho Salmon freshwater productivity and smolt (marine) survival for Coho Salmon from Black Creek, Vancouver Island.

46.3. References

Zimmerman, M.S., Irvine, J.R., O'Neill, M., Anderson, J.H., Greene, C.M., Weinheimer, J., Trudel, M., and Rawson, K. 2015. Spatial and temporal patterns in smolt survival of wild and hatchery coho salmon in the Salish Sea. Marine and Coastal Fisheries 7(1): 116-134, DOI: 10.1080/19425120.2015.1012246

Summaries from the Poster Session

47. MONITORING PLUVIAL WATERSHED DYNAMICS ON THE CENTRAL COAST (CALVERT ISLAND): SENSOR AND SAMPLING DATA FROM 2013 TO 2015

Ian J.W. Giesbrecht[1], Bill Floyd[2,1], Maartje Korver[1], Brian Hunt[3,1], Ken Lertzman[4,1], Allison Oliver[5,1] and Suzanne Tank[5]

[1]Hakai Institute, Calvert Island, B.C., Ian@hakai.org
[2]B.C. Ministry of Forests, Lands and Natural Resource Operations *and* Vancouver Island University, Nanaimo, B.C.
[3]University of British Columbia, Vancouver, B.C.
[4]Simon Fraser University, Burnaby, B.C.
[5]University of Alberta, Edmonton, AB.

47.1. Highlights

- We characterize watershed conditions in the 2014-2015 water year (October through September) in comparison to 2013-2014, using initial data from one of seven new observatory watersheds on Calvert Island, on the Central Coast of British Columbia.
- Rainfall and stream discharge data show that 2014-2015 was wetter than 2013-2014 overall, yet mid-summer was drier.
- Stream temperatures were elevated in mid-summer of 2015 relative to 2014.
- Freshwater and dissolved organic carbon exports to the coastal ocean were higher in 2014-2015 than the previous year.

47.2. Introduction

A long-term coastal margin observatory was established by the Hakai Institute on the B.C. Central Coast in 2013. The goal of the research program (the Kwakshua Watersheds Program) is to understand watershed interactions with the coastal ocean, with a focus on the generation and flux of organic matter from the outer-coast landscape. The core measurements are also broadly relevant to monitoring freshwater conditions for anadromous fish on the Central Coast and freshwater influences on the nearshore Pacific Ocean. Here we briefly characterize watershed conditions in the 2014-2015 water year (October through September) in comparison to 2013-2014, with emphasis on watershed 708 (Figure 47-1) where we have the longest record of observations.

47.3. Methods

47.3.1. Study Area

The observatory is located on Calvert and Hecate Islands on the outer-coast of central British Columbia (Figure 47-1). Mean annual precipitation from 1980 to 2010 is estimated at >3000 mm, primarily as rain (ClimateWNA, Wang et al. 2012). Our focal watersheds vary in size from 317 ha to 1279 ha. Elevations range from 0 to 1012 m above sea level. Wetlands are extensive, including blanket bogs and forested wetlands. Tree sizes and growth rates are small compared to more mountainous areas of the mainland coast. These watersheds are broadly representative of the many small outer-coast watersheds that drain directly into the Pacific Ocean from Vancouver Island to Southeast Alaska.

47.3.2. Data Collection

We used a network of in-situ sensors to monitor weather and stream conditions (Figure 47-1). Water chemistry samples were collected approximately once per month on average through the focal time period. Salt-dilution stream gauging and stream stage sensors were used to build rating curves and to estimate freshwater discharge on 5 min intervals. Weather and stream data are presented for watershed 708, a 780 ha watershed draining directly into Kwakshua channel.

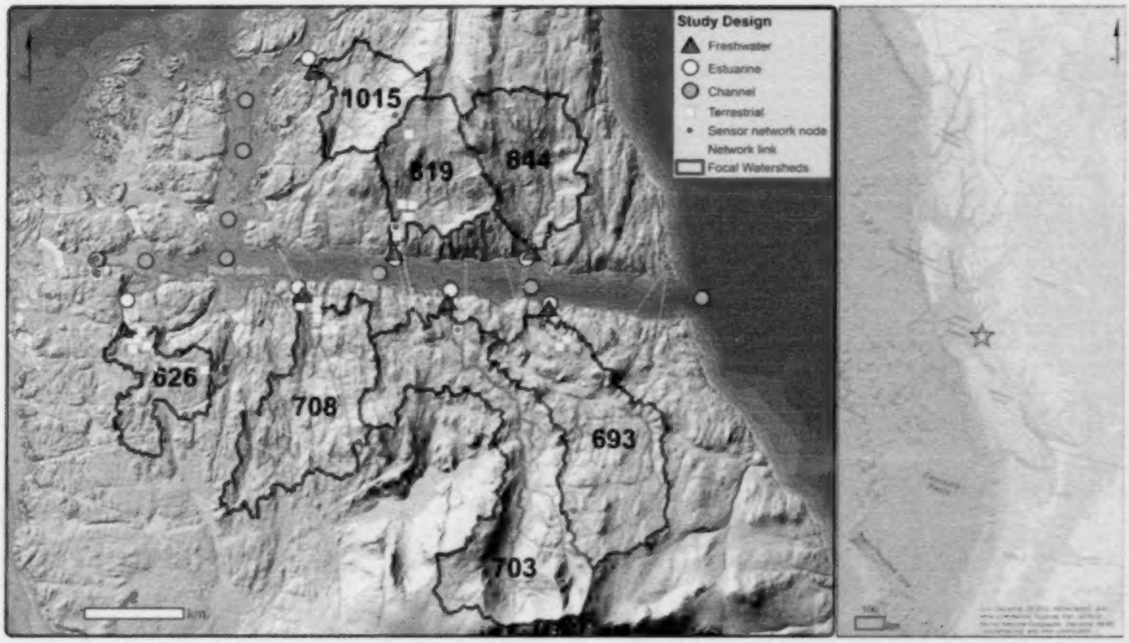

Figure 47-1. Location and design of the Hakai Institute's coastal margin observatory on Calvert Island, on the Central Coast of British Columbia. The seven focal watersheds (boundaries and ID numbers shown) drain into Kwakshua Channel. A network of weather, terrestrial, stream and ocean monitoring sites was established in 2013. The bare-earth hillshade was produced from a LiDAR derived digital elevation model.

47.4. Results

Over the full record of observation, stream stage is tightly coupled with rainfall in this flashy coastal watershed (Figure 47-2). Fall-winter is very wet, yet stream level rises and falls distinctly with each storm. Much lower stream levels are observed in late summer / early fall when rainfall is at a minimum.

The watershed received substantially more rainfall in 2014-2015 (2657 mm) than in 2013-2014 (1939 mm) (Figure 47-3), resulting in more freshwater outflow (Figure 47-4). Similarly, in 2014-2015 we observed a larger export of dissolved organic carbon (DOC) than in 2013-2014 (data not shown; Oliver et al. In prep.). Greater outflows of water (and DOC) were particularly evident in October-November, January and August-September (Figure 47-5).

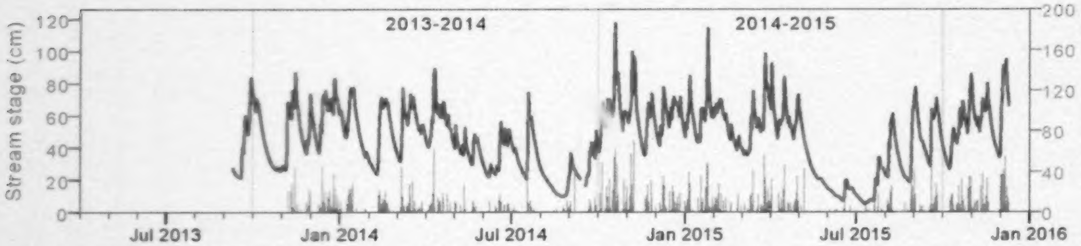

Figure 47-2. Rainfall and stream stage time series for watershed 708, from the date of establishment. Grey reference lines define the water years used in this report.

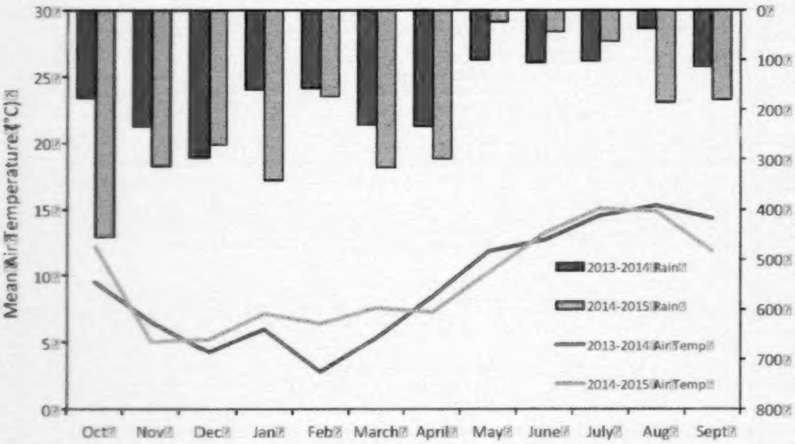

Figure 47-3. Rainfall and air temperature at the outlet of watershed 708 in 2013-2014 and 2014-2015.

Despite 2014-2015 being a wetter year overall, mid-summer rainfall (Figure 47-3) and discharge estimates (Figure 47-5) were substantially less than in 2013-2014. In the dry mid-summer of 2015, we also observed elevated stream temperatures compared to 2014 (Figure 47-6). However, rain events in August and September of 2015 brought stream discharge values well above those observed in the same months of 2014. Thus, in 2015 the summer low flow period began and ended earlier than in the previous year. Similarly, the period of elevated stream temperatures began and ended earlier in 2015.

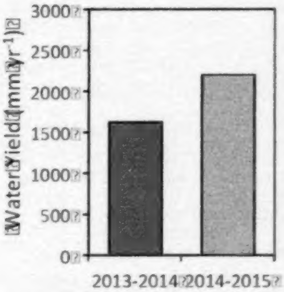

Figure 47-4. Freshwater outflow to the coastal ocean from watershed 708 in 2013-2014 and 2014-2015, expressed as discharge per unit area (yield).

Results from watershed 708 on Calvert Island suggest that freshwater conditions and exports from small outer-coast watersheds are sensitive to changes in water inputs from year to year. We observed weather driven changes in the seasonality of stream flow and stream temperature, in addition to inter-annual differences in the total annual export of water and dissolved organic carbon. Analyses are underway to explore the drivers of terrestrial carbon flux and to evaluate the dynamics of terrestrial contributions to the marine foodweb and the coastal carbon cycle.

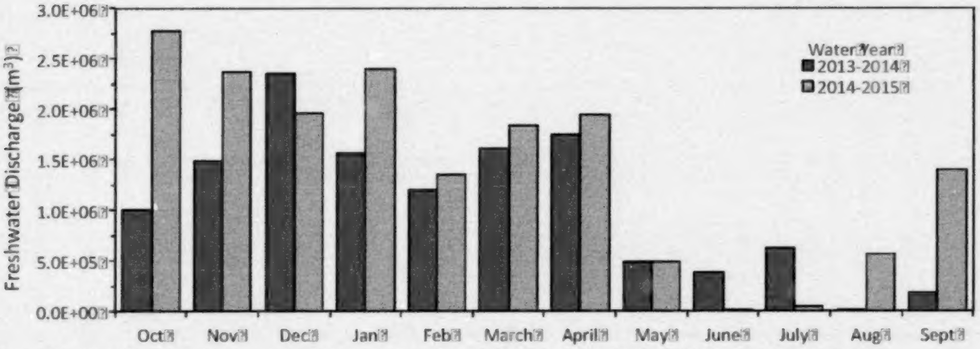

Figure 47-5. Monthly discharge totals for watershed 708 in 2013-2014 and 2014-2015.

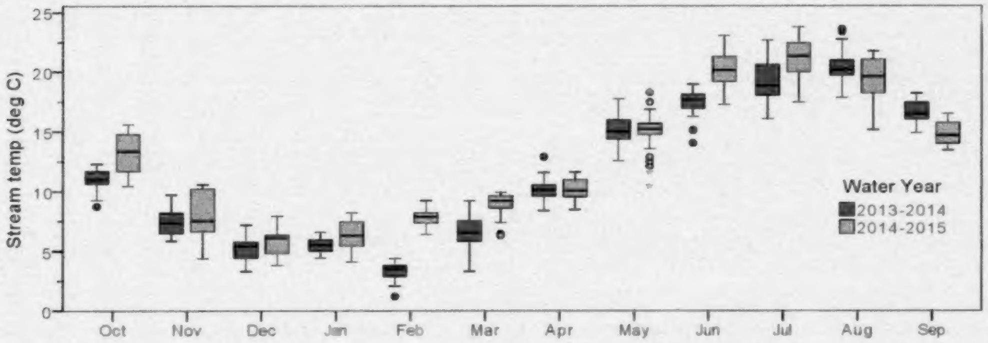

Figure 47-6. Box plots of stream temperature at watershed 708 in 2013-2014 and 2014-2015.

47.5. References

Wang, T., Hamann, A., Spittlehouse, D. and Murdock, T. 2012. ClimateWNA – High-resolution spatial climate data for western North America. Journal of Applied Meteorology and Climatology, 51: 16-29.

48. FOOD FOR THOUGHT: ZOOPLANKTON AND SALMON SURVIVAL IN THE SALISH SEA

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48.1. Highlights

- Zooplankton have been identified as being the most significant current data gap for the Salish Sea Marine Survival Project.
- Our project provides a comprehensive zooplankton monitoring program to identify the seasonal status and trends of the species composition, biomass and abundance of these animals in the Strait of Georgia.

48.2. Summary

Zooplankton have been identified as being the most significant current data gap for the Salish Sea Marine Survival Project. Zooplankton are the basis of the food web for juvenile salmon and are the direct connection between environmental factors and salmon survival and growth. Historically it has been difficult to link variations in zooplankton to variations in salmon populations.

Our project provides a comprehensive zooplankton monitoring program to identify the seasonal status and trends of the species composition, biomass and abundance of these animals in the Salish Sea. The central questions are: What physical oceanographic and plankton processes control the seasonal and inter-annual variability in zooplankton timing, amount and composition? And what is the role of zooplankton in determining the growth and survival of juvenile salmon in the Salish Sea?

With the help of the Pacific Salmon Foundation, we have been able to collect an unprecedented 443 zooplankton samples in 2015 (Figure 48-1). Sampling platforms included Citizen Science, charter, and DFO vessels. This is the most intensive plankton sampling effort in the Strait of Georgia ever, with sampling conducted every 2 weeks from February to October.

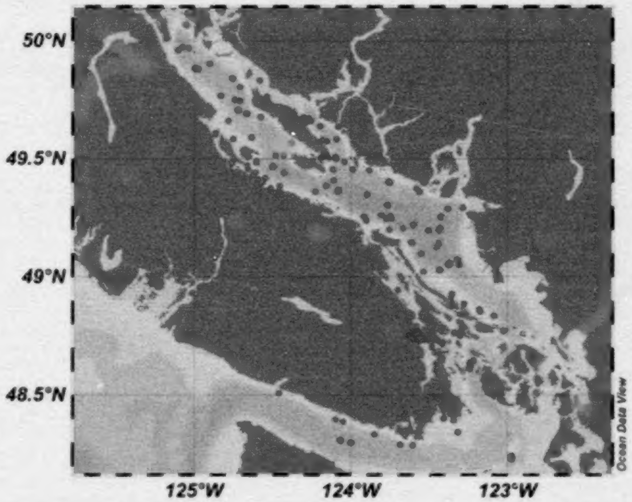

Figure 48-1. Strait of Georgia zooplankton sample locations in 2015.

These samples will allow us to describe the changes in zooplankton species communities (e.g. Figure 48-2) and biomass within the Salish Sea during 2015, a year with unusual warming conditions, with the ultimate goal to compare these results with variations in the marine survival of juvenile salmon in this region.

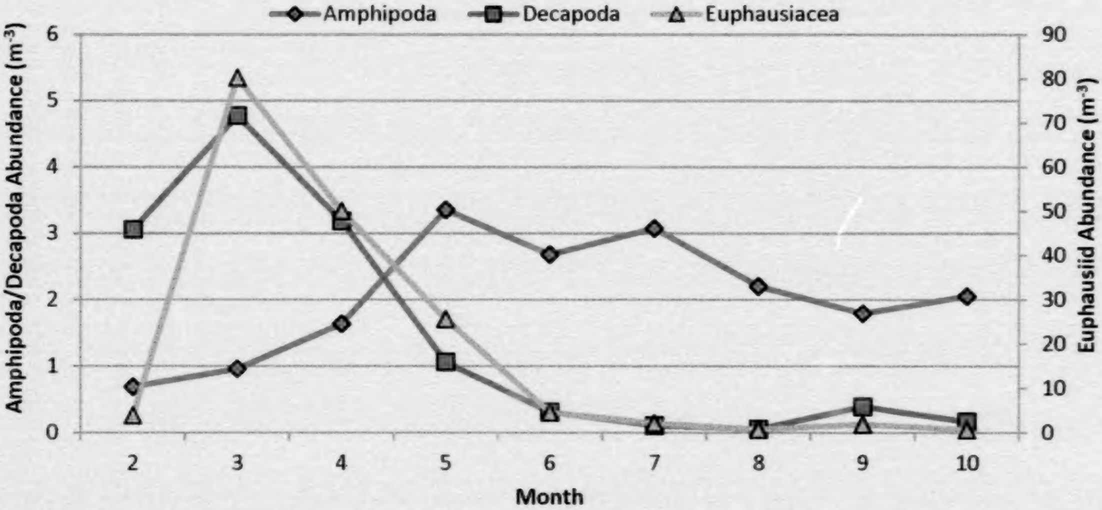

Figure 48-2. Average abundances of select zooplankton prey of juvenile salmon in 2015 from the Strait of Georgia

49. QUANTIFYING CLIMATE-DEPENDENT AND ANTHROPOGENIC IMPACTS ON ECOSYSTEM SERVICES IN THE SUBARCTIC PACIFIC OCEAN

Robert Izett[1], Philippe Tortell[1], Roger Francois[1], Evgeny Pakhomov[1,2], John Dower[3], Michael Dowd[4] and William Cheung[2]

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[2]Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, B.C., epakhomo@eos.ubc.ca, w.cheung@fisheries.ubc.ca
[3]School of Earth and Ocean Sciences, University of Victoria, B.C., dower@uvic.ca
[4]Department of Mathematics and Statistics, Dalhousie University, NS, Michael.Dowd@Dal.Ca

49.1. Highlights

- The NSERC funded Strategic Grant Program aims to quantify key ecosystem services (fisheries production and carbon export) in the Subarctic Pacific Ocean and characterize their responses to climate variability and anthropogenic disturbances.
- Observations from Line P, La Perouse and High Seas cruises over the next three years (2016-2018) will be coupled with hydrographic survey data from the Central B.C. Coast (collected by the Hakai Institute) to improve estimates of primary and secondary production, carbon export, and fisheries yields.
- Ecosystem change and resilience will be quantified against background variability to investigate the links between climate change, planktonic and carbon dynamics, and fish production.
- Regional satellite algorithms and climate-fisheries models will be refined using field data, enabling enhanced ecosystem-based monitoring and assessment of the marine ecosystems' response to climate variability.

49.2. Overview

An NSERC Strategic Grant Program has been funded to quantify key ecosystem services (fisheries production and carbon export) in the Subarctic Northeast Pacific Ocean, and characterize their responses to climate forcing and anthropogenic disturbances. The project represents a strategic partnership between universities and DFO, providing advanced monitoring tools for evaluating large-scale environmental impacts on ecosystem services of the Subarctic Pacific Ocean. The project is divided into five modules led by university-based principle investigators (PIs): Primary Productivity (P. Tortell), Carbon Export Flux (R. Francois), Trophic Transfer and Fisheries Yield (E. Pakhomov and J. Dower), Environmental Statistics (M. Dowd), and Climate-Fisheries Models (W. Cheung). By combining new observational data, remote sensing, advanced statistical analyses and numerical models, we seek to better understand climate-driven variability of marine production, leading to enhanced fisheries stock assessments and improved ecosystem-based management.

49.3. Program Objectives

The overall objective is to quantify and characterize the responses of fisheries production and CO_2 uptake/carbon export to climate variability in the Subarctic NE Pacific Ocean. We aim to understand linkages across multiple trophic levels, and use new data on lower trophic level processes to improve fisheries stock assessments, ecosystem models and carbon flux estimates under current and future climate states. We will make progress towards this goal by developing new observational and modeling tools to address the following specific objectives:

1. Improve the spatial-resolution of phytoplankton biomass and productivity measurements.

2. Quantify vertical carbon fluxes and CO_2 uptake capacity.

3. Refine existing satellite algorithms to derive regional estimates of net primary productivity, carbon export and phytoplankton taxonomic composition.

4. Evaluate the functional relationships between phytoplankton and zooplankton biomass/productivity, and the population dynamics of key fish stocks.

5. Detect meaningful ecosystem change in the presence of natural variability and non-linear environmental forcing.

6. Develop improved ecosystem models exploring potential long-term climate change impacts on Subarctic Pacific fisheries productivity.

49.4. Approaches

The research plan involves a coupling between robust field sampling techniques, state-of-the-art measurement devices, remote sensing, and advanced statistical analyses and ecosystem models. Sea-going autonomous instrumentation (e.g. membrane inlet mass spectrometer, oxygen optode, gas tension device, fast-repetition rate fluorometer, and particulate backscatter device) will be deployed on Line P and La Perouse survey cruises over the next three years. Discrete measurements of surface and water column carbon export flux (by integrative measurement of ^{234}Th deficits), secondary production (Chitobiase assay), phytoplankton (HPLC) and zooplankton (laser optical plankton counter and bongo and multi-net tows) taxonomic composition and abundance, and hydrographic properties will also be obtained on future oceanographic cruises. Supplementary analyses of plankton taxonomy and productivity, fish abundance, and seawater hydrography will be conducted onboard High Seas research cruises, and through the perennial Hakai Institute and Continuous Plankton Recorder monitoring programs. An ultimate goal is to use the field measurements to calibrate regional satellite algorithms of primary productivity, phytoplankton taxonomic composition, and carbon export. Additionally, the field data will be used to fine-tune parameterizations of climate-fisheries models (i.e. Ecopath with Ecosim). Assessment of the Subarctic NE Pacific Ocean's response and resilience to environmental forcing will involve advanced statistical analyses (including trend analysis, non-stationarity time series methods, multivariate spatial regression, and Bayesian methods) of field, historical, and satellite data. Planktonic systems, carbon dynamics and fish stocks will be linked and evaluated.

We aim to provide a new suite of environmental monitoring tools (i.e. satellite products, and statistical/ecosystem models). Subsequent application of these tools by DFO scientists and managers will facilitate enhanced ecosystem-based monitoring by improving stock assessments and return predictions of Sockeye Salmon and Pacific Herring in Subarctic NE Pacific Ocean.

49.5. Collaborators

In addition to the PIs, collaborators include Alvain, S. (CNRS), Batten, S. (Sir Alister Hardy Foundation), Behrenfeld, M. J. (OSU), Forrest, R. (DFO), Grant, S. (DFO), Hunt, B. H. (Hakai), Irvine, J. (DFO), Miller, L. A. (DFO), Perry, I. R., (DFO), Trudel, M. (DFO), additional DFO Oceanographic Researchers and Applied Scientists, Post-Doctoral Researchers and Graduate Students.

50. HAKAI INSTITUTE'S GROWING MARINE SENSOR NETWORK

Wayne Jacob*, Brian Hunt, Wiley Evans, Rhea Smith and Shawn Hateley, Hakai Institute, Quadra Island, B.C., *wayne@hakai.org

50.1. Highlights

- The Hakai Institute has established an expandable marine sensor network utilizing a common data portal data.hakai.org.
- The marine network is integrated with an existing terrestrial sensor network that uses a common, easily expandable telemetry backbone.

50.2. Hakai Institute's Marine Sensor Network

Starting in 2015 a coordinated network of ocean monitoring stations for Hakai Institute has been established to compliment the growing dataset from existing ocean profiling equipment and discrete sampling that inform our ocean monitoring studies. Several long term autonomous monitoring stations have been established between Quadra and Calvert Islands to provide high resolution and continuous monitoring of marine conditions through a range of environments critical to many marine species.

All of our real time sensors are integrated with a large well established terrestrial network of environmental sensors utilizing Campbell Scientific based telemetry systems. This integrated system currently includes over 70 sensor arrays and is easily expandable as out sensor network continues to grow.

Data from our devices are routed to our online data portal data.hakai.org where users can view in near real time the data streams in graphical and tabular formats. Other data formats from our stand alone loggers and discrete sampling programs are added to the data warehouse as they become available.

50.2.1. Temperature Loggers

Hakai Institute deployed an array of 30 Tidbit V2 temperature data loggers throughout the Central Coast, B.C. These will provide high resolution surface temperature data over a large spatial coverage supporting and increase our understanding of how species abundance is influenced by ocean temperatures spatially, seasonally and temporally with climate change. The array includes a range of important habitats, including herring and salmon spawning areas, kelp forests and seagrass beds.

Linear models will investigate the relationship between temperature and sample data for marine species including plankton, seaweeds, seagrass and their associated microbial, invertebrate and vertebrate communities.

50.2.2. Heriot Bay, B.C. Flow-Through System

A flow-through continuous monitoring system (FTS) has been deployed at Heriot Bay, Quadra Island in August 2015 where seawater drawn from a depth of 5 m is pumped through a manifold containing a collection of marine sensors. Data is captured on a Campbell Scientific CR1000 data logger and sent to the Hakai data portal for incorporation into the data warehouse data.hakai.org. Over the next year data quality control and assurance methods will be employed to provide high resolution, high quality data from this monitoring station. This prototype system may be installed in several other facilities along Johnstone Straight and in the Central Coast, B.C. to support our research initiatives.

50.2.3. Burke-O-Lator CO2 Systems

Dr. Wiley Evans leads the installation and operations of surface water carbonate chemistry monitoring systems, which include Burke-O-Lator pCO_2/TCO_2 analyzers at sites in Seward and Ketchikan, Alaska, and in Heriot Bay, B.C., a Shipboard Underway pCO_2 Environmental Recorder (Super-CO_2) that will roam between vessels-of-opportunity and eventually deployed at the Bamfield Marine Science Center late this year, and a General Oceanics pCO_2 Measuring System to be deployed in May 2016 on the Alaska Marine Highway Ferry M/V Columbia operating between Bellingham, Washington and Skagway, Alaska twice per month.

The Burke-O-Lator pCO_2/TCO_2 analyzers provide real time data as well as capacity to measure carbonate parameters in discrete samples. This capacity allows us to incorporate direct carbonate system measurements into our oceanographic work at targeted "core" stations. In addition to the direct CO_2 measurements, these data in combination with dissolved oxygen and nitrate measurements allow for the development of dissolved oxygen or nitrate based empirical algorithms that will then be applied to the LIMPET cabled underwater observatory data streams and CTD profiles for expanded space/time resolution of CO_2 properties across the Hakai network.

50.2.4. LIMPET Cabled Underwater Observatory

In October 2015 Hakai Institute deployed its first cabled seafloor observatory platform called LIMPET. This prototype observatory incorporates a SeaBird SBE37 CTD(P) recorder providing real time data from 70 cm off the seafloor. The observatory is located at Heriot Bay, Quadra Island in approximately 21 m of water. The structure designed by Colby Owens of Hakai Energy Solutions is made up of 1 inch stainless steel tubing for a light weight, but stable base which can easily be deployed by small vessels. A media converter and Campbell Scientific CR1000 data logger are encased in a Prevco Inc. underwater enclosure which feeds data to our telemetry network via a 350 m long hybrid coax cable.

50.2.5. Integration of the Sensor Network

The marine sensor network was designed to be incorporated into the existing terrestrial sensor network which includes approximately 70 sensor nodes over a large spatial extent. The standardization of data logging and telemetry equipment facilitates high resolution and near real time data availability, as well as providing a scalable infrastructure. The data outputs from these real time sensor arrays can be incorporated with data from CTD profiles and other autonomous systems in the Hakai data warehouse, where researchers can access the data in various formats. All raw/original data is available to view publically, however data product download is by permission. Requests for data products can be submitted to data@hakai.org.

Appendix 1. Review Meeting Agenda

March 1 and 2, 2016
Nanaimo River Room, Vancouver Island Conference Centre, Nanaimo B.C.

Co-Chairs: Ian Perry (Ian.Perry@dfo-mpo.gc.ca)
Peter Chandler (Peter.Chandler@dfo-mpo.gc.ca)

Organizer: Stephanie King (king@seathisconsulting.com, 250-734-3569)

DRAFT AGENDA – Tuesday, March 1st (Conditions in the NE Pacific and outer BC coast)

Start	Presenter	Presentation
9:30-9:40	Peter Chandler/Ian Perry	Welcome, introductions and purpose
9:40-9:45	Carmel Lowe	Welcome from DFO
9:45-10:00	Faron Anslow	Analysis on land surface conditions
10:00-10:15	Tetjana Ross	El Niño, the Blob and another warmest year
10:15-10:30	Marie Robert/Doug Yelland	Results from the Line P and La Perouse oceanographic surveys
10:30-10:45	Angelica Peña	Results from phytoplankton monitoring in the WCVI and Line P
10:45-11:00	**Break (refreshments provided)**	
11:00-11:15	Sonia Batten	Indices of lower trophic levels for the west coast and offshore, from the Continuous Plankton Recorder survey
11:15-11:30	John Holmes	The summer travels of Albacore Tuna in 2014 and 2015
11:30-11:45	Roy Hourston	Wind-driven upwelling/downwelling along the West Coast in 2015
11:45-12:00	Bill Crawford	Oxygen concentrations on the west coast of Vancouver Island
12:00-12:15	Jim Gower	NE Pacific satellite and wave buoy time series
12:15-12:30	Peter Chandler	Sea surface temperature and salinity at BC lighthouses in 2015
12:30-13:15	**Lunch**	
13:15-13:30	Anne Ballantyne	Sea Level on the BC coast
13:30-13:45	Moira Galbraith	Zooplankton along the BC continental margin 2015
13:45-14:00	Ian Perry	Small mesh multispecies trawl survey results for 2015 along WCVI
14:00-14:15	Jennifer Boldt	Herring and other pelagic fish in BC
14:15-14:30	Marc Trudel	Update on juvenile salmon off the West Coast
14:30-14:45	Chelsea Stanley	Findings from the 2015 Pacific Hake population survey with NOAA
14:45-15:00	**Break**	
15:00-15:15	Kim Hyatt	Status of coast-wide Sockeye salmon indicator stocks in 2015 and outlook for returns in 2016-2018
15:15-15:30	Howard Stiff	Ocean state changes and variations in environmental conditions affecting Sockeye salmon in the terminal marine area of Alberni Inlet in 2015
15:30-15:45	Mark Hipfner	Observations on seabirds along the outer coast
15:45-16:00	Linda Nichol	Fin whales off the north coast
16:00-16:15	Jeff Marliave	Seasonal variability in ocean conditions along a shallow reef on the Howe Sound/Strait of Georgia boundary
16:15-16:30	Peter Chandler/Ian Perry	General discussion
16:30-18:00	**Ocean Networks Canada** is hosting a poster session and mixer after the meeting at the VICC. Please stay to enjoy the posters and some light snacks. There will also be a cash bar for those who are interested.	

Group dinner at the Old City Station Pub

DRAFT AGENDA – Wednesday, March 2nd (Coastal and freshwater conditions)

Start	Presenter	Presentation
9:00-9:15	Peter Chandler/Ian Perry	Reflections on day 1, key highlights and new ideas
9:15-9:30	Andres Cisneros	Trends in Canadian marine research, 1900-2015: current state and research gaps
9:30-9:45	Brian Hunt	Hakai Oceanography Program: update on the Central Coast and Strait of Georgia time series
9:45-10:00	Peter Chandler	SoG water properties in 2015
10:00-10:15	Akash Sastri	Sea-surface and deep water properties in the Strait of Georgia during 2015: Ferries and cabled instruments
10:15-10:30	Wiley Evans	A novel carbonate system time series from a highly resolved site in the northern Strait of Georgia
10:30-10:45	**Break (refreshments provided)**	
10:45-11:00	Susan Allen	SoG spring bloom 2015 and 2016
11:00-11:15	Maycira Costa	Ocean colour in the Strait
11:15-11:30	Chrys Neville	Strait of Georgia juvenile salmon in 2015
11:30-11:45	Ian Perry	Indicators of system changes in the Strait of Georgia
11:45-12:00	Dave Jackson	Update on survey coverage, new tools, seabed classification
12:00-12:30	Andrew Day/Karin Bodtker	CORI presentation and discussion
12:30-13:15	**Lunch**	
13:15-13:30	Ian Perry/Andrew Day	Discussion
13:30-13:45	Erin Rechisky	Telemetry-based estimates of early marine survival and residence time of juvenile steelhead in the Strait of Georgia and Queen Charlotte Strait, 2015
13:45-14:00	Sue Grant	Fraser River Sockeye : Abundance, productivity trends, and return forecasts
14:00-14:15	Chuck Parken	Trends of Chinook salmon abundance in fisheries managed under the Pacific Salmon Treaty
14:15-14:30	Kim Hyatt	Interactions between state changes in freshwater systems and salmon return variations
14:30-14:45	**Break**	
14:45-15:00	Scott Akenhead	Applying freshwater metadata in stock-recruit models for Chilko Lake Sockeye Salmon
15:00-15:15	Eddie Loos	A satellite-based time series of chlorophyll in Chilko Lake and application to Sockeye Salmon
15:15-15:30	Dave Patterson	2015 Fraser River environmental conditions and variation in Sockeye Salmon survival
15:30-15:45	Jim Irvine	Salish Sea Coho Salmon declines – Is the problem in the ocean or fresh water?
15:45-17:00	Peter Chandler/Ian Perry	**Take away messages and wrap-up**

Posters (16:30 to 18:00 on March 1 in the Newcastle Lobby at the VICC)

Susan Allen- NEMO+RUBRA a 3-D coupled biophysical model of the SoG

William Atlas - Sockeye salmon life-cycle and environmental monitoring in the Koeye watershed, Central Coast: 2013-2015

Ian Giesbrecht - Monitoring pluvial watershed dynamics on the Central Coast (Calvert Island): sensor and sampling data from 2013 to 2015

Alexander Hare - Hakai Institute Salmon Early Marine Survival Program

Mark Halverson - Aspects of the HF radar-measured surface M2 tides near the Fraser River plume in the Strait of Georgia, BC

Margot Hessing-Lewis - Integrated nearshore habitat monitoring in British Columbia

Robert Izett - Quantifying marine productivity across multiple trophic levels in the NE Pacific

Wayne Jacob - Hakai Institute Marine Sensor Network

Kellogg et al. - InFORMative Science: Monitoring the arrival of Fukushima contamination on the Canadian Coast

Stephanie King and Jim Gower – Monitoring surface waters in the Salish Sea: 2015 results

Kang Wang - Hakai Institute Oceanography Program Overview

Kelly Young, Ian Perry and Moira Galbraith - Food For Thought: Zooplankton and Salmon Survival in the Salish Sea

Appendix 2. Review Meeting Participants

Participant	Affiliation
Scott Akenhead	Ladysmith Institute, Ladysmith
Hussein Alidina	WWF
Susan Allen	University of British Columbia, Vancouver
Faron Anslow	University of Victoria, Victoria
Mary Arai	Emeritus Scientist, DFO, PBS, Nanaimo
Andres Araujo	DFO, PBS, Nanaimo
Stephanie Archer	DFO, PBS, Nanaimo
Sandy Argue	Argus Bio-Resources, Victoria
Dan Baker	Vancouver Island University, Nanaimo
Anne Ballantyne	DFO, IOS, Sidney
Sonia Batten	Sir Alister Hardy Foundation for Ocean Science, Nanaimo
Douglas Bertram	Environment Canada, Institute of Ocean Science, Sidney
David Blackbourn	DFO, Retired
Karin Bodtker	Coastal Ocean Research Institute at the Vancouver Aquarium
Jennifer Boldt	DFO, PBS, Nanaimo
Laura Borden	Vancouver Aquarium, Vancouver
Leslie Brown	ASL Environmental Sciences, Sidney
Davon Callander	DFO, PBS, Nanaimo
Barron Carswell	Province of British Columbia, Ministry of Agriculture
Dennis Chalmers	Province of British Columbia, Ministry of Agriculture
Peter Chandler	DFO, IOS, Sidney
Andrés Cisneros	University of British Columbia, Vancouver
Steven Colwell	DFO, IOS, Sidney
Maycira Costa	University of Victoria, Victoria
Garth Covernton	Vancouver Island University, Nanaimo
Bill Crawford	DFO (retired), IOS, Sidney
Stuart Crawford	Haida Oceans Technical Team
Shaun Davies	DFO, North Coast
Andrew Day	Coastal Ocean Research Institute at the Vancouver Aquarium
John Dower	University of Victoria, Victoria
Sarah Dudas	Vancouver Island University, Nanaimo
Stephanie Duff	Vancouver Island University, Nanaimo
Andrew Edwards	DFO, PBS, Nanaimo
Wiley Evans	Hakai Institute, Campbell River
Linnea Flostrand	DFO, PBS, Nanaimo
Michael Folkes	DFO, PBS, Nanaimo
Moira Galbraith	DFO, IOS, Sidney
Ian Giesbrecht	Hakai Institute
Jim Gower	DFO, IOS, Sidney
Sue Grant	DFO, Delta
Ben Grupe	DFO, Institute of Ocean Science, Sidney
Dana Haggarty	University of British Columbia, Vancouver
Nicky Haigh	Vancouver Island University, Nanaimo

Mark Halverson	University of British Columbia, Vancouver
Charles Hannah	DFO, IOS, Sidney
Alex Hare	Hakai Institute
Doug Hay	DFO, retired
Carly Haycroft	Province of British Columbia
Margot Hessing-Lewis	Hakai Institute
Joy Hillier	DFO, Prince Rupert
Mark Hipfner	Canadian Wildlife Service, Delta
John Holmes	DFO, PBS, Nanaimo
Roy Hourston	DFO, IOS, Sidney
Brian Hunt	Hakai Institute
Kim Hyatt	DFO, PBS, Nanaimo
Jim Irvine	DFO, PBS, Nanaimo
Robert Izett	University of British Columbia, Vancouver
Dave Jackson	DFO, CHS, IOS, Sidney
Jennifer Jackson	Hakai Institute
Wayne Jacob	Hakai Institute
Greg Jones	Environment Canada, IOS, Sidney
Stephanie King	Sea This Consulting, Nanaimo
Jackie King	DFO, PBS, Nanaimo
Lynn Lee	Parks Canada
Linxie Jie Liu	University of British Columbia, Vancouver
Joanne Liutkus	BC Salmon Farmers Association
Erika Loc	Environment Canada, Canadian Wildlife Service
Eddie Loos	ASL Environmental Sciences, Sidney
Carmel Lowe	DFO, Regional Director, Science
Jason Mahoney	DFO, Salmon Enhancement (Burrard St.)
Amy Mar	DFO, A/ Regional Manager, Oceans Program
Jeff Marliave	Vancouver Aquarium, Vancouver
Jim McIsaac	T. Buck Suzuki Foundation, Vancouver
Skip McKinnell	PICES (retired)
Kristi Miller	DFO, PBS, Nanaimo
Ken Morgan	No affiliation
Karina Ramos Musalem	University of British Columbia, Vancouver
Jessica Nephin	DFO, Institute of Ocean Science, Sidney
Chrys Neville	DFO, PBS, Nanaimo
Linda Nichol	DFO, PBS, Nanaimo
Athena Ogden	DFO, PBS, Nanaimo
Greig Oldford	DFO, RHQ
Liz Oliphant	DFO, CHS, IOS, Sidney
Elise Olson	University of British Columbia, Vancouver
Stephen Page	DFO, IOS, Sidney
Evgeny Pakhomov	University of British Columbia
Emma Pascoe	University of Victoria, Victoria
Bruce Patten	DFO, PBS, Nanaimo
Dave Patterson	DFO, SFU

Rich Pawlowicz	University of British Columbia, Vancouver
Isobel Pearsall	Pacific Salmon Foundation, Vancouver
Angelica Peña	DFO, IOS, Sidney
Ian Perry	DFO, PBS, Nanaimo
Eric Peterson	Hakai Institute
Erin Rechisky	Kintama Research Services, Nanaimo
Kendra Robinson	DFO, SFU
Andrew Ross	DFO, IOS, Sidney
Tetjana Ross	DFO, IOS, Sidney
Shani Rousseau	DFO, Institute of Ocean Sciences, Sidney
Akash Sastri	Ocean Networks Canada, Victoria
Steven Schut	DFO, Science advisor
Dan Selbie	DFO, Cultus Lake
Brent Seymour	DFO, CHS, IOS, Sidney
Ellie Simpson	Simon Fraser University
Lara Sloan	DFO, Communications Advisor
Chelsea Stanley	DFO, IOS, Sidney
Jennifer Steele	DFO, RHQ
Howard Stiff	DFO, PBS, Nanaimo
Margot Stockwell	DFO, PBS, Nanaimo
Arlene Tompkings	DFO, PBS, Nanaimo
Marc Trudel	DFO, PBS, Nanaimo
Strahan Tucker	DFO, PBS, Nanaimo
Theresa Venello	University of Victoria, Victoria
Brenda Waddell	DFO, PBS, Nanaimo
Kang Wang	University of British Columbia, Vancouver
Bill Wareham	David Suzuki Foundation
David Welch	Kintama Research Services, Nanaimo
Cecilia Wong	Environment Canada
Roger Wysocki	DFO, Fisheries Science - Pacific and Arctic Section
Doug Yelland	DFO, IOS, Sidney
Kelly Young	DFO, IOS, Sidney
Fancis Zwiers	University of Victoria, Victoria